# SOIL ORGANIC MATTER IN SUSTAINABLE AGRICULTURE

Edited by

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# 8 Tillage and Residue Management Effects on Soil Organic Matter

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## CONTENTS



## TYPES OF TILLAGE

Soil tillage is an ancient practice that was originally used to eradicate weeds and loosen the soil for planting seeds (Lal, 2001). In modern agriculture, tillage is still performed for controlling weeds, insects, and diseases; improving the soil's physical condition by loosening compacted layers and enhancing soil warming in spring; incorporating fertilizer, herbicide, and plant residues; conserving soil and water; and preparing a quality seedbed (Jones et al., 1990). The type of tillage employed should be designed to achieve a specific set of goals. During the past several decades, conservation tillage, and, particularly, no tillage have been increasingly utilized, as the need for inversion tillage has been reevaluated. The susceptibility of inverted soil to wind and water erosion has highlighted the environmental and production threats to sustainability (Figure 8.1). The term *conservation tillage* includes a variety of systems, all designed to minimize residue incorporation with the intent of abating soil erosion. According to the definition of the term by the United States Department of Agriculture (USDA), >30% residue cover must be on the soil surface immediately after planting (Figure 8.2). A major part of this chapter compares the influences of conservation and inversion tillage on soil organic matter.

Tillage practices range from the very simple to the very complex. Buckingham (1976) and Swinford (1994) give excellent descriptions of the types of tillage operations and their intended use. This chapter focuses on four groups of tillage practices affecting soil organic matter dynamics:

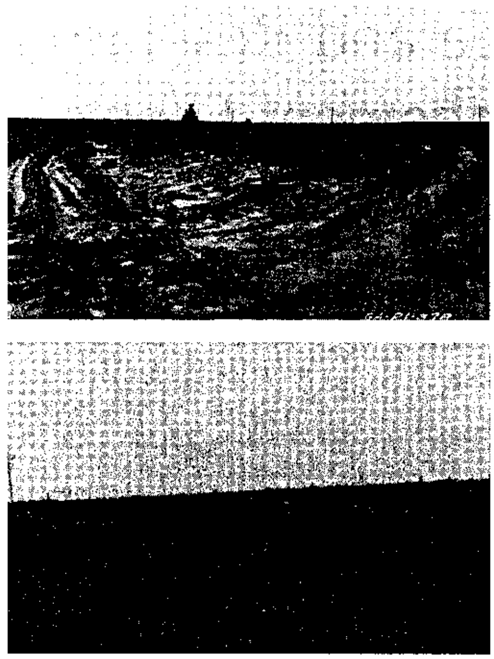

FIGURE 8.1 Wind and water erosion are serious threats to the sustainability of agriculture. Both these erosive forces preferentially displace the lighter organic matter fraction from the soil surface, resulting in a decline of long-term productivity. Photos depict water erosion in the Georgia Piedmont and wind erosion in the loess hills of Nebraska.

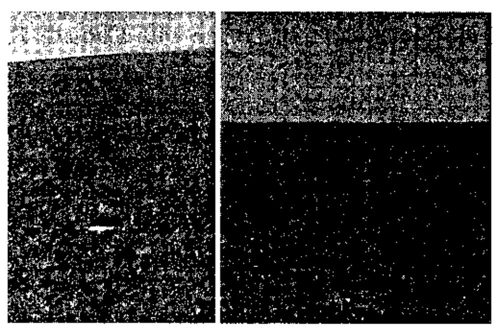

FIGURE 8.2 Alfalfa is an excellent sod component of long-term rotations that can help abate erosion. Traditionally, sod was broken by plowing and smoothing before planting maize, leaving the soil surface exposed to erosive forces (left). With no tillage, sod is killed with herbicides and maize can be grown without soil disturbance (right). Photos from eastern Nebraska.

moldboard plow, shallow, ridge, and no tillage. The moldboard plow was perhaps the most widely used primary tillage implement during the early part of the 20th century (Allmaras et al., 2000). The moldboard plow inverts soil to a depth of usually 15 to 30 cm, resulting in complete burial of aboveground crop residues. Secondary tillage operations of disking or harrowing, or both, are often needed to prepare a suitable seedbed following plowing.

Shallow tillage is accomplished by using a wide diversity of implements to scarify the soil surface. One primary tillage tool that has replaced the moldboard plow in some regions is the chisel plow. Although the working depth of the chisel plow might be similar to that of the moldboard plow, the degree of soil inversion with the chisel plow is much less. In semiarid regions with small grains as the main crop, primary tillage operations can be accomplished with an offset disk or field cultivator. Working depth of these implements is often less than that with plow tools, e.g., 10 to 15 cm depth. The extent of residue incorporation depends on the number of passes performed.

A conservation-tillage method with greater opportunities for controlling traffic is ridge tillage. The extent of soil disturbance varies greatly with the type of equipment and number of cultivations with this system. Ridges are typically formed, the tops scraped off to create a clean seedbed, and ridges reshaped during summer cultivation. The negative effects of machinery traffic can be limited to the same rows year after year so that the majority of the field is not compacted.

No tillage relies completely on herbicides and management to control weeds. Planting operations are typically the only disturbance to the soil surface.

## TYPES OF RESIDUE MANAGEMENT

If residues of various crops are considered a by-product without much value and a hindrance to future production, they can be removed from the field by burning. Residues can also be removed from the field as valuable fodder for animals or as materials for construction. Removal of residues either by burning or by harvest has important implications for soil organic matter dynamics. Crop residues are rich in organic C and N, and therefore their removal is a loss of input to the soil, resulting almost always in a decline in soil organic matter compared with retention of residues (Saffigna et al., 1989; Dalal et al., 1991; Kapkiyai et al., 1999).

Residues left in the field ultimately undergo decomposition with a majority of the C respired back to the atmosphere as $CO_2$ and a smaller fraction retained as soil organic matter. The rate and extent of residue transformation into soil organic matter depends on the type, quantity, and quality of residues produced and how and when residues are manipulated. The quantity of residues depends on climatic, soil, and fertility variables. The quality of residues depends on the plant species (e.g., small grain straw low in N vs. legume cover crop forage rich in N) and developmental stage when killed. Residues of primary crops can be cut, shredded, or left standing in the field. Cover crops can be allowed to mature, mowed, rolled, or terminated with herbicides. No-tillage management with a dense mat of previous crop residues can be effective at controlling erosion and weeds and moderate temperature and moisture fluctuations (Figure 8.3).

**FIGURE 8.3** Cotton planted with no tillage following harvest of barley in the Georgia Piedmont.

## EFFECT OF TILLAGE ON PLANT GROWTH

Agronomic production of food and fiber is a vocation that brings both joys and challenges to those called to be stewards of the land (Figure 8.4). For those who farm the land, nature can be both friend and foe. With care and management, the fruits of the earth can be harvested in bounty. However, the desire to obtain more from the land is often limited by the harsh realities of weather and pestilence. Those who believe that they know their system are often taught new lessons by nature, neighbors, accountants, or the government. Modern agricultural production is a complicated system involving natural resources, technology, finance, ingenuity, labor, and social fabric. There will always be different systems of agricultural production requiring different solutions to problems.

Soil erosion is a natural disaster that damages resources in a slow but continuous, and, occasionally, dramatic manner. Exposure of the fragile surface soil to the erosive forces of wind and water without protective cover has led to long-term soil, water, and air degradation (Trimble, 1974). Conservation tillage systems attempt to mimic nature by allowing residues that fall to the surface to remain there without mechanical incorporation. Seeds can then be planted directly through this mulch layer with minimal disturbance to the protective surface cover. This approach was partly made possible with the development of herbicides, which reduced one of the greatest needs for tillage, i.e., weed control.

Changes in microclimate under conservation compared with inversion tillage systems result in more water available for crop uptake by (1) getting more precipitation to infiltrate soil rather than run off of the land and (2) reducing evaporation of water from the soil surface during intervals between precipitation events (Lascano et al., 1994). Lack of tillage, however, could result in excessive compaction of soil, especially in systems with heavy equipment and random traffic patterns. In many studies, soil immediately below the surface becomes compacted during early adoption of no tillage, a process that could limit root growth and development. In the long term, however, freezing–thawing and bioperturbation loosen soil under no tillage compared with plow tillage (Voorhees and Lindstrom, 1984). It is also possible that old root channels and worm holes that remain intact without soil disturbance enhance water infiltration and root growth without a major change in bulk density.

**FIGURE 8.4** Statue of St. Isidore, the patron saint of farmers, in Bow Valley, Nebraska.

FIGURE 8.5 Side-by-side long-term experiment near College Station, TX, comparing conventional disk-and-bed tillage of sorghum on left with no tillage of sorghum on right.

Many short-term studies and a few long-term studies have evaluated the effect of tillage system on plant productivity (Figure 8.5). In 33 comparisons with small grains, yield under no-tillage systems was equivalent to that under shallow-tillage systems (Table 8.1). However, yield under plow tillage was, on average, lower than under shallow or no tillage. At many of the semiarid locations, water conservation with shallow- or no-tillage management probably contributed to improved yield. From a compilation of studies with various crops other than maize or small grains, similar effects of tillage systems on yield occurred (Table 8.2). However, from a compilation of studies with maize, tillage system had no overall effect on yield (Table 8.3). Individual experiments might have shown significant reductions or increases in yield with adoption of conservation tillage, but on average there was no negative or positive effect of conservation tillage on maize yield. The lack of tillage system effect on yield might be important in promoting conservation tillage to control soil erosion and improve water quality in a particular watershed or region. No yield reduction can make conservation tillage attractive because, other than the initial investment in modifying or purchasing a conservation-tillage planter, operating costs are often lower with conservation-tillage systems than with conventional-tillage systems (Jones et al., 1990).

In the long term, accumulation of soil organic matter under conservation-tillage systems should lead to an increase in the storage and potential availability of nutrients. On a Fluventic Ustochrept in Texas, the N fertilizer required to achieve 95% of maximum sorghum grain yield was 40 to 60% higher during the first year of no-tillage management compared with conventional tillage (Figure 8.6). With time, however, the N fertilizer required became similar between tillage systems. It could be expected that during the second decade of no-tillage management, N fertilizer requirement would be lower than under conventional tillage. Although higher initial fertilizer expenditures might be needed to achieve optimum yield with no-tillage management because of sequestration of nutrients into organic matter, the long-term benefits of sustained nutrient storage, enhanced water infiltration and retention, improved soil biological activity, and more stable production can more than offset the initial costs. Cropping systems that include legumes with substantial biological N-fixation could help offset any additional requirement for N fertilizer inputs in conservation-tillage systems. In a long-term tillage study on a Typic Fragiudalf in Ohio, maize and soybean yields tended to increase with time (18 years) under no tillage compared with conventional tillage (Dick et al., 1991). On a very poorly drained Mollic Ochraqualf, yields were lower under no tillage than under conventional tillage during early years, but became similar between tillage systems with time. Similar positive changes in yield under no tillage compared with conventional tillage occurred with time in long-term studies in Maryland and Kentucky (Bandel and Meisinger, 1993; Ismail et al., 1994). Other studies that indicate negative yield effects of conservation tillage compared with conventional tillage have often been limited by weed control (Brandt, 1992), diseases due to crop sequencing (Dick et al., 1991), or poor seedling establishment due to straw management (Cannell and Hawes, 1994).

**TABLE 8.1**
**Comparison of Small Grain Yield (g $m^{-2}$) among Tillage Systems**

| Crop/Component | Location | Observations | Conditions | Soil | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Spr wheat – grain | Montana | 10 | Continuous spring wheat | Argiboroll | — | 155 | — | 176 | Aase et al. (1995) |
| Spr wheat – grain | North Dakota | 48 | Spring wheat–fallow | Argiboroll | 119 | 118 | — | 116 | Black and Tanaka (1997) |
| Spr wheat – grain | North Dakota | 48 | Wheat–wheat–sunflower | Argiboroll | 131 | 145 | — | 145 | Black and Tanaka (1997) |
| Spr wheat – grain | SK, Canada | 2 | Continuous wheat | Haploboroll | — | 256 | — | 245 | Curtin et al. (2000) |
| Spr wheat – grain | SK, Canada | 2 | Wheat–fallow | Haploboroll | — | 280 | — | 256 | Curtin et al. (2000) |
| Win wheat – grain | North Dakota | 48 | Wheat–wheat–sunflower | Argiboroll | 169 | 188 | — | 199 | Black and Tanaka (1997) |
| Win wheat – grain | New Mexico | 1 | 2-year sorghum–fallow–wheat | Paleustoll | — | 202 | — | 271 | Christensen et al. (1994) |
| Win wheat – grain | Texas | 12 | Continuous wheat | Ustochrept | — | 277 | — | 247 | Franzluebbers et al. (1995a) |
| Win wheat – grain | Texas | 12 | Wheat/soybean | Ustochrept | — | 371 | — | 361 | Franzluebbers et al. (1995a) |
| Win wheat – grain | Texas | 12 | Sorghum–wheat/soybean | Ustochrept | — | 385 | — | 407 | Franzluebbers et al. (1995a) |
| Win wheat – grain | Colorado | 12 | Wheat–fallow | Paleustoll | — | 289 | — | 279 | Halvorson et al. (1997) |
| Win wheat – grain | Austria | 5 | 9-year rotation | Chernozem | 498 | 493 | — | | Kandeler et al. (1999) |
| Win wheat – grain | Texas | 3 | 0 g N $m^{-2}$ | Haplustoll | — | 218 | — | 134 | Knowles et al. (1993) |
| Win wheat – grain | Texas | 3 | 5 g N $m^{-2}$ | Haplustoll | — | 277 | — | 221 | Knowles et al. (1993) |
| Win wheat – grain | Texas | 3 | 9 g N $m^{-2}$ | Haplustoll | — | 328 | — | 272 | Knowles et al. (1993) |
| Win wheat – grain | Texas | 3 | 14 g N $m^{-2}$ | Haplustoll | — | 349 | — | 331 | Knowles et al. (1993) |
| Win wheat – grain | Texas | 10 | Continuous wheat | Paleustoll | — | 95 | — | 114 | Schomberg and Jones (1999) |
| Barley – grain | BC, Canada | 10 | Continuous barley | Cryoboralf | — | 300 | — | 309 | Arshad et al. (1999a) |
| Barley – grain | AB, Canada | 3 | 2-year barley with canola/pea | Cryoboralf | — | 342 | — | 370 | Arshad et al. (1999b) |
| Barley – grain | U.K. | 3 | Continuous barley | Cambisol | 624 | 640 | — | 668 | Ball et al. (1989) |
| Barley – grain | U.K. | 3 | Continuous barley | Gleysol | 611 | 625 | — | 680 | Ball et al. (1989) |
| Spr wheat – straw | North Dakota | 48 | Spring wheat–fallow | Argiboroll | 177 | 176 | — | 176 | Black and Tanaka (1997) |
| Spr wheat – straw | North Dakota | 48 | Wheat–wheat–sunflower | Argiboroll | 224 | 248 | — | 266 | Black and Tanaka (1997) |
| Spr wheat – straw | SK, Canada | 12 | Continuous wheat | Haploboroll | — | 191 | — | 191 | Campbell et al. (1999) |
| Spr wheat – straw | SK, Canada | 12 | Wheat-fallow | Haploboroll | — | 248 | — | 235 | Campbell et al. (1999) |
| Spr wheat – straw | SK, Canada | 12 | Continuous wheat | Haploboroll | — | 288 | — | 287 | Campbell et al. (1995) |
| Spr wheat – straw | SK, Canada | 6 | Wheat–fallow | Haploboroll | — | 364 | — | 348 | Campbell et al. (1995) |
| Spr wheat – straw | SK, Canada | 11 | Continuous wheat | Haploboroll | — | 158 | — | 163 | Campbell et al. (1996) |

| Crop/Component | Location | Observations | Conditions | Soil | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Spr wheat – straw | SK, Canada | 6 | Wheat–fallow | Haploboroll | — | 300 | — | 314 | Campbell et al. (1996) |
| Spr wheat – straw | SK, Canada | 2 | Continuous wheat | Haploboroll | — | 464 | — | 431 | Curtin et al. (2000) |
| Spr wheat – straw | SK, Canada | 2 | Wheat–fallow | Haploboroll | — | 514 | — | 440 | Curtin et al. (2000) |
| Win wheat – straw | North Dakota | 8 | Wheat–wheat–sunflower | Argiboroll | 287 | 324 | — | 346 | Black and Tanaka (1997) |
| Win wheat – straw | Texas | 10 | Continuous wheat | Paleustoll | — | 244 | — | 310 | Schomberg and Jones (1999) |
| Barley – straw | AB, Canada | 3 | 2-year barley with canola/pea | Cryoboralf | — | 551 | — | 551 | Arshad et al. (1999b) |
| Plow vs. shallow tillage ($Pr > F = 0.02$) | | | | | 316 | 329 | — | — | $n = 9$ |
| Plow vs. no tillage ($Pr > F = 0.01$) | | | | | 293 | — | — | 325 | $n = 8$ |
| Shallow vs. no tillage ($Pr > F = 0.80$) | | | | | — | 300 | — | 299 | $n = 33$ |

*Note*: Spr wheat, spring wheat; Win wheat, winter wheat.

**TABLE 8.2**
**Comparison of Various Other Crop Yields (g $m^{-2}$) among Tillage Systems**

| Crop/Component | Location | Observations | Conditions | Soil | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Sorghum – grain | New Mexico | 3 | 2-year sorghum–fallow–wheat | Paleustoll | — | 297 | — | 314 | Christensen et al. (1994) |
| Sorghum – grain | Texas | 12 | Continuous sorghum | Ustochrept | — | 503 | — | 468 | Franzluebbers et al. (1995a) |
| Sorghum – grain | Texas | 12 | Continuous sorghum | Ustochrept | — | 519 | — | 453 | Franzluebbers et al. (1995a) |
| Sorghum – grain | Georgia | 2 | Sorghum–soybean | Rhodudult | 318 | — | — | 379 | Groffman et al. (1987) |
| Sorghum – grain | Austria | 2 | 9-year rotation | Chernozem | 600 | 586 | — | — | Kandeler et al. (1999) |
| Sorghum – grain | Texas | 10 | Continuous sorghum | Paleustoll | — | 293 | — | 293 | Schomberg and Jones (1999) |
| Sorghum – grain | Texas | 3 | Wheat–sorghum–sunflower | Paleustoll | 256 | 244 | — | 334 | Unger (1984) |
| Sorghum – straw | Georgia | 2 | Sorghum–soybean | Rhodudult | 783 | — | — | 762 | Groffman et al. (1987) |
| Sorghum – straw | Texas | 10 | Continuous sorghum | Paleustoll | — | 413 | — | 431 | Schomberg and Jones (1999) |
| Sorghum – straw | Texas | 3 | Wheat–sorghum–sunflower | Paleustoll | 394 | 501 | — | 469 | Unger (1984) |
| Soybean – grain | Ohio | 20 | Maize–soybean | Fragiudalf | 163 | — | — | 193 | Dick et al. (1991) |
| Soybean – grain | Ohio | 20 | Maize–soybean | Ochraqualf | 230 | — | — | 199 | Dick et al. (1991) |
| Soybean – grain | Alabama | 4 | Continuous soybean | Hapludult | 164 | 203 | — | 239 | Edwards et al. (1988) |
| Soybean – grain | Alabama | 4 | Maize–soybean | Hapludult | 222 | 263 | — | 266 | Edwards et al. (1988) |
| Soybean – grain | Alabama | 4 | Maize-wheat/soybean | Hapludult | 241 | 245 | — | 216 | Edwards et al. (1988) |
| Soybean – grain | Texas | 12 | Continuous soybean | Ustochrept | — | 176 | — | 145 | Franzluebbers et al. (1995a) |
| Soybean – grain | Iowa | 1 | Maize–soybean: 10 years | Haplaquoll | 324 | 283 | 299 | — | Singh et al. (1992) |
| Soybean – grain | Minnesota | 1 | Maize–soybean: 10 years | Hapludoll | 239 | 273 | — | 218 | Singh et al. (1992) |
| Soybean – grain | North Carolina | 5 | Maize–soybean | Kanhapludult | — | 235 | — | 254 | Wagger and Denton (1992) |
| Soybean – grain | North Carolina | 5 | Maize–soybean | Hapludult | — | 245 | — | 245 | Wagger and Denton (1992) |
| Sunflower – seed | North Dakota | 8 | Wheat–wheat–sunflower | Argiboroll | 131 | 140 | — | 138 | Black and Tanaka (1997) |
| Sunflower – seed | Texas | 3 | Wheat–sorghum–sunflower | Paleustoll | 155 | 163 | — | 154 | Unger (1984) |
| Sunflower – straw | North Dakota | 8 | Wheat–wheat–sunflower | Argiboroll | 296 | 312 | — | 319 | Black and Tanaka (1997) |
| Pea – grain | Austria | 1 | 9-year rotation | Chernozem | 508 | 453 | — | — | Kandeler et al. (1999) |
| Sugar beet | Austria | 1 | 9-year rotation | Chernozem | 5170 | 5375 | — | — | Kandeler et al. (1999) |
| Plow vs. shallow tillage ($Pr > F = 0.19$) | | | | | 669 | 695 | | | $n = 13$ |
| Plow vs. no tillage ($Pr > F = 0.07$) | | | | | 276 | | | 299 | $n = 13$ |
| Shallow vs. no tillage ($Pr > F = 0.66$) | | | | | — | 296 | — | 292 | $n = 17$ |

**TABLE 8.3**
**Comparison of Maize Yield (g m$^{-2}$) among Tillage Systems**

| Crop/Component | Location | Observations | Conditions | Soil | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Maize – grain | Ohio | 20 | Continuous maize | Fragiudalf | 545 | — | — | 672 | Dick et al. (1991) |
| Maize – grain | Ohio | 20 | Maize–soybean | Fragiudalf | 656 | — | — | 778 | Dick et al. (1991) |
| Maize– grain | Ohio | 20 | Continuous maize | Ochraqualf | 702 | — | — | 686 | Dick et al. (1991) |
| Maize – grain | Ohio | 20 | Maize–soybean | Ochraqualf | 603 | — | — | 515 | Dick et al. (1991) |
| Maize – grain | Alabama | 4 | Continuous maize | Hapludult | 850 | 803 | — | 810 | Edwards et al. (1988) |
| Maize – grain | Alabama | 4 | Maize–soybean | Hapludult | 819 | 897 | — | 857 | Edwards et al. (1988) |
| Maize – grain | Alabama | 4 | Maize–wheat/soybean | Hapludult | 819 | 899 | — | 872 | Edwards et al. (1988) |
| Maize – grain | Indiana | 7 | Continuous maize | Haplaquoll | 1092 | 1047 | 1047 | 947 | Griffith et al. (1988) |
| Maize – grain | Indiana | 7 | Maize–soybean | Haplaquoll | 1182 | 1163 | 1191 | 1136 | Griffith et al. (1988) |
| Maize – grain | Indiana | 7 | Continuous maize | Ochraqualf | 825 | 846 | 824 | 882 | Griffith et al. (1988) |
| Maize – grain | Indiana | 7 | Maize–soybean | Ochraqualf | 821 | 837 | 876 | 933 | Griffith et al. (1988) |
| Maize – grain | Kentucky | 20 | Continuous: 0 g N m$^{-2}$ | Paleudalf | 477 | — | — | 429 | Ismail et al. (1994) |
| Maize – grain | Kentucky | 20 | Continuous: 8 g N m$^{-2}$ | Paleudalf | 682 | — | — | 677 | Ismail et al. (1994) |
| Maize – grain | Kentucky | 20 | Continuous: 17 g N m$^{-2}$ | Paleudalf | 711 | — | — | 750 | Ismail et al. (1994) |
| Maize – grain | Kentucky | 20 | Continuous: 34 g N m$^{-2}$ | Paleudalf | 732 | — | — | 757 | Ismail et al. (1994) |
| Maize – grain | Iowa | 12 | Continuous maize | Hapludoll | 805 | 782 | 752 | 741 | Karlen et al. (1991) |
| Maize – grain | Iowa | 12 | Maize–soybean | Hapludoll | 876 | 881 | 856 | 863 | Karlen et al. (1991) |
| Maize – grain | Pennsylvania | 3 | Alfalfa–maize: 0 g N m$^{-2}$ | Hapludult | 674 | — | — | 707 | Levin et al. (1987) |
| Maize– grain | Pennsylvania | 3 | Alfalfa–maize: 5 g N m$^{-2}$ | Hapludult | 701 | — | — | 771 | Levin et al. (1987) |
| Maize – grain | Pennsylvania | 3 | Alfalfa–maize: 9 g N m$^{-2}$ | Hapludult | 727 | — | — | 798 | Levin et al. (1987) |
| Maize – grain | Pennsylvania | 3 | Alfalfa–maize: 14 g N m$^{-2}$ | Hapludult | 756 | — | — | 802 | Levin et al. (1987) |
| Maize – grain | Pennsylvania | 3 | Alfalfa–maize: 18 g N m$^{-2}$ | Hapludult | 732 | — | — | 817 | Levin et al. (1987) |
| Maize – grain | Texas | 1 | Continuous maize | Ustochrept | — | 978 | 1021 | — | McFarland et al. (1991) |
| Maize – grain | New York | 2 | Various cover and nitrogen | Hapludalf | 542 | | — | 485 | Sarrantonio and Scott (1988) |
| Maize – grain | Iowa | 1 | Continuous maize: 10 years | Haplaquoll | 941 | 799 | 700 | — | Singh et al. (1992) |
| Maize – grain | Minnesota | 1 | Maize-soybean: 10 years | Haplaquoll | 824 | 876 | — | 795 | Singh et al. (1992) |
| Maize – grain | North Carolina | 5 | Continuous maize | Kanhapludult | — | 403 | — | 593 | Wagger and Denton (1992) |

*continued*

**TABLE 8.3 (continued)**
**Comparison of Maize Yield (g $m^{-2}$) among Tillage Systems**

| Crop/Component | Location | Observations | Conditions | Soil | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Maize – grain | North Carolina | 4 | Maize–soybean | Kanhapludult | — | 317 | — | 474 | Wagger and Denton (1992) |
| Maize – grain | North Carolina | 5 | Continuous maize | Hapludult | — | 797 | — | 845 | Wagger and Denton (1992) |
| Maize – grain | North Carolina | 4 | Maize–soybean | Hapludult | — | 628 | — | 690 | Wagger and Denton (1992) |
| Maize – straw | New York | 2 | Various cover and nitrogen | Hapludalf | 529 | — | — | 491 | Sarrantonio and Scott (1988) |
| Maize – silage | QC, Canada | 11 | Continuous maize silage | Haplaquept | 981 | 975 | 1029 | — | Angers et al. (1995) |
| Maize – silage | New York | 2 | Continuous maize | Haplaquept | 1473 | — | 1538 | — | Mataruka et al. (1993) |
| Maize – silage | Michigan | 2 | Alfalfa–maize: 0 g N $m^{-2}$ | Hapludalf | 518 | — | — | 510 | Rasse and Smucker (1999) |
| Maize – silage | Michigan | 2 | Alfalfa–maize: 12 g N $m^{-2}$ | Hapludalf | 876 | — | — | 704 | Rasse and Smucker (1999) |
| Plow vs. shallow tillage (Pr > F = 0.89) | | | | | 903 | 900 | — | — | $n = 12$ |
| Plow vs. ridge tillage (Pr > F = 0.53) | | | | | 1000 | — | 979 | — | $n = 9$ |
| Plow vs. no tillage (Pr > F = 0.78) | | | | | 744 | — | — | 748 | $n = 27$ |
| Ridge vs. no tillage (Pr > F = 0.79) | | | | | — | — | 924 | 917 | $n = 6$ |
| Shallow vs. no tillage (Pr > F = 0.43) | | | | | — | 798 | — | 817 | $n = 14$ |

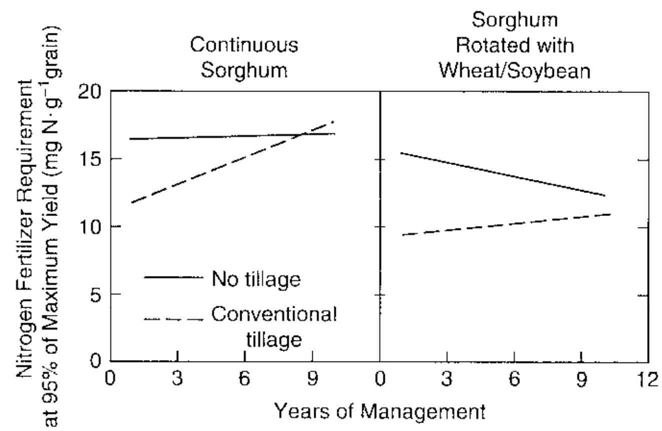


**FIGURE 8.6** Calculated N fertilizer requirement to achieve 95% of maximum sorghum grain yield each year during the first 10 years of a long-term tillage study in southcentral Texas. Yield response was derived from N fertilizer application rates of 0, 4.5, 9.0, and 13.5 g $m^{-2}$ $year^{-1}$. (Data from Franzluebbers, A.J. et al. 1995a. *Plant Soil* 173:55–65.)

The implication from this compilation of studies is that higher or equal crop yield under conservation tillage compared with inversion tillage will lead to, on average, higher or equal C inputs into the soil system.

## EFFECTS OF DISTURBANCE/TILLAGE ON SOIL ORGANIC MATTER

### Depth Distribution of Organic Matter

Inversion tillage mixes organic residues with soil at deeper depths. The type of tillage tool greatly influences the eventual location of aboveground residues within the soil profile. Allmaras et al. (1996) showed that moldboard plowing to a depth of 25 cm buried 70% of the aboveground oat residue at a depth of 12–24 cm, whereas chisel plowing to a depth of 15 cm left nearly 60% of the residue at a depth of 0–6 cm (Figure 8.7). Obviously, no tillage would leave nearly all of the residue at or above the soil surface. Because plant residues contribute greatly to subsequent soil organic matter formation, the placement of plant residues with different tillage practices is of utmost importance for understanding the depth distribution of soil organic matter.

With repeated inversion tillage, soil organic matter becomes uniformly distributed within the plowed layer (Figure 8.8). The fate of organic matter mixed into soil vs. that left on the soil surface depends on the prevailing climatic conditions. In general, however, the environment within soil is more buffered against extremes in moisture and temperature than that at the soil surface. Higher moisture content in soil than on the soil surface is probably the biggest factor that leads to greater decomposition of organic matter in tilled soil (Franzluebbers et al., 1996a).

Surface-placed crop residues under conservation tillage systems experience frequent drying and rewetting, depending on precipitation events. Although decomposition of surface-placed residues is slower than that of buried residues (Brown and Dickey, 1970; Douglas et al., 1980; Wilson and Hargrove, 1986; Ghidey and Alberts, 1993), N concentration of remaining residues can increase with time relative to buried residues (Varco et al., 1993; Franzluebbers et al., 1994c). Typically, higher N concentration residues leads to faster decomposition of residues (Vigil and Kissel, 1991). This contradiction suggests that frequent drying and rewetting of surface-placed residues increases the resistance of certain N compounds to microbial decomposition (Franzluebbers et al., 1994c), which leads to higher total N accumulation in the surface of no-tillage soils. However, during

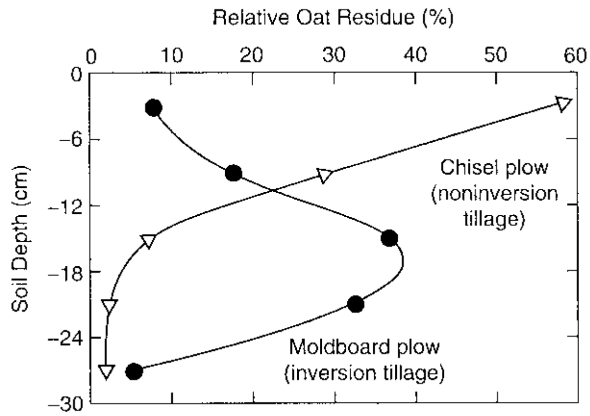


**FIGURE 8.7** Oat residue distribution in soil following moldboard plow and chisel plow in Minnesota. (Data from Allmaras, R.R. et al. 1996. *Soil Sci. Soc. Am. J.* 60:1209–1216.)

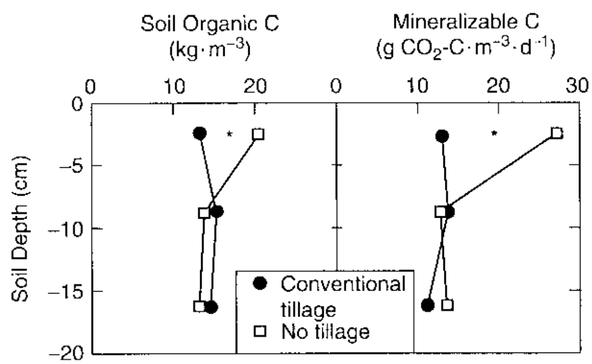


**FIGURE 8.8** Depth distribution of soil organic C and mineralizable C at the end of 9 years under conventional disk-and-bed tillage and no tillage in southcentral Texas. * indicates significance between tillage systems at $p < 0.1$. (Data from Franzluebbers, A.J. et al. 1994a. *Soil Sci. Soc. Am. J.* 58:1639–1645.)

decomposition of buried and surface-placed canola residues, the portion of total N remaining as lignin-bound N increased, but was not different between the two environments (Figure 8.9). More work is needed to understand the transformations that occur during decomposition of various crop residues under different micro- and macroclimatic conditions.

Organic matter has a direct impact on the density of soil and therefore on the content of organic matter within a given volume of soil. Because conservation tillage systems leave residues near the soil surface, most investigations report a substantial change in soil organic matter in surface soil as compared with inversion-tillage systems. However, calculation of net change in soil organic matter with a change in tillage management should be made to at least the depth of the tillage tool in both systems. At the end of 4 years of management in a Typic Kanhapludult in Georgia, soil organic C under no tillage was higher than under disk tillage (15-cm depth) at a depth of 0 to 2.5 cm, but not different at lower depths (Figure 8.10). C content was 81% higher (although C concentration was 95% higher) with no tillage than with disk tillage at a depth of 0 to 2.5 cm. Similarly, C content was only 2% lower with no tillage (C concentration was 14% lower) than with disk tillage at a depth of 2.5 to 7.5 cm. Summation of C content to a depth of 15 cm indicated no difference between tillage systems because of counteracting effects of residue placement at lower

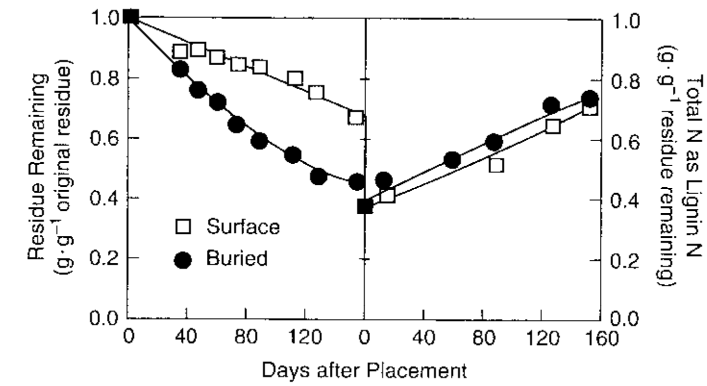


**FIGURE 8.9** Canola residue mass and the fraction of total N in remaining residue as lignin-bound N during field incubation in Alberta, Canada, when placed on the surface or buried at 10 cm. (Data from Franzluebbers, A.J., and Arshad, M.A. 1996a. *Soil Sci. Soc. Am. J.* 60:1422–1427.)

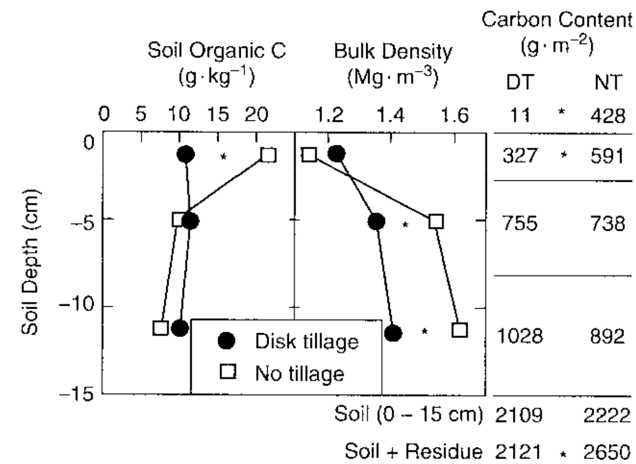


**FIGURE 8.10** Depth distribution of soil organic C concentration, soil bulk density, and C content at the end of 4 years under conventional disk tillage and no tillage in the Georgia Piedmont. * indicates significance between tillage systems at $p < 0.1$. (Data from Franzluebbers, A.J. et al. 1999. *Soil Sci. Soc. Am. J.* 63:349–355.)

depths with disk tillage. However, including surface residue C with soil organic C to a depth of 15 cm resulted in significantly greater storage of C under no tillage compared with disk tillage.

Stratification of soil organic matter pools with depth under conservation tillage systems has consequences on soil functions beyond that of potentially sequestering more C in soil. The soil surface is the vital interface that receives much of the fertilizers and pesticides applied to cropland, receives the intense impact of rainfall, and partitions the fluxes of gases and water into and out of soil. Surface organic matter is therefore essential to erosion control, water infiltration, and conservation of nutrients, all important soil functions. No-tillage management of a 2.7-ha cropped watershed for 24 years on a Typic Kanhapludult in Georgia reduced water runoff to 22 mm year$^{-1}$ compared with 180 mm year$^{-1}$ under previous management of the watershed under conventional inversion tillage (Endale et al., 2000). Soil loss was even more dramatically reduced with no-tillage management (3 vs. 129 kg ha$^{-1}$ mm$^{-1}$ runoff). A greenhouse study to separate the short- and long-term effects of disturbance on soil hydraulic properties of the same soil revealed that doubling soil organic C content in freshly tilled soil improved water infiltration by 27% (Franzluebbers, 2002b). However, water infiltration was 3.3 times higher in intact cores from long-term conservation tillage with a high degree of soil organic matter stratification compared with intact cores from a long-term conventionally tilled soil (but untilled during the previous 14 months) with a low degree of soil organic matter stratification.

Stratification of soil organic matter with conservation tillage depends on the inherent level of soil organic matter, intensity of disturbance, type of cropping system, and length of time. In an analysis of stratification ratios (soil organic C in the surface 5 cm divided by that at 12.5- to 20-cm depth) under no tillage in three different ecoregions, there were greater differences in the stratification of soil organic C between tillage systems in hot, wet, low soil organic matter environments than in cold, dry, high soil organic matter environments (Figure 8.11). Soils with low inherent levels of organic matter can be the most functionally improved with conservation tillage, despite modest or no change in total standing stock of soil organic C within the rooting zone. Alternatively, soils with inherently high soil organic matter even under conventional-tillage management would likely obtain relatively little additional soil functional benefit with adoption of conservation tillage, because inherent soil properties would be at a high level.

Stratification ratio of particulate organic C in a Typic Kanhapludult in Georgia decreased along a disturbance gradient created by tillage tools with different inversion characteristics (Figure 8.12). Less intensive mixing of soil preserves crop residues and soil organic matter near the soil surface, where it has the most beneficial impact. Stratification of mineralizable C in a Fluventic Ustochrept in Texas increased with increasing cropping intensity under conventional tillage, but was always higher under no tillage (Figure 8.13). More intensive cropping increases the quantity of residues produced, which can lead to higher soil organic matter. Stratification ratio of soil organic C (0- to 2.5-cm divided by 12.5- to 20-cm depth) in an Aquic Hapludult in Maryland was 1.0 under plow tillage and increased with time under no tillage to 1.1 at 1 year, 1.4 at 2 years, and 1.5 at 3 years (McCarty et al., 1998).

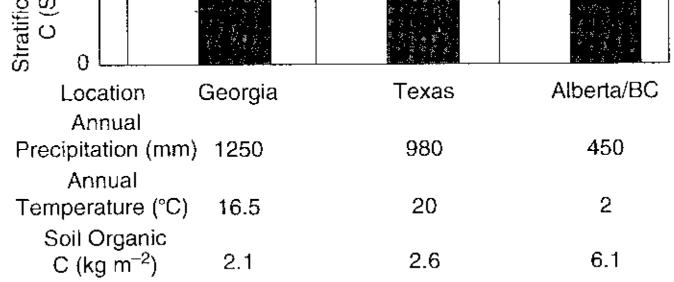


**FIGURE 8.11** Stratification ratio of soil organic C under conventional and no tillage at three locations differing in climatic characteristics and standing stock of soil organic C. *** indicates significance between tillage systems at $p < 0.001$. (Data from Franzluebbers, A.J. 2002a. *Soil Tillage Res.* 66:95–106.)

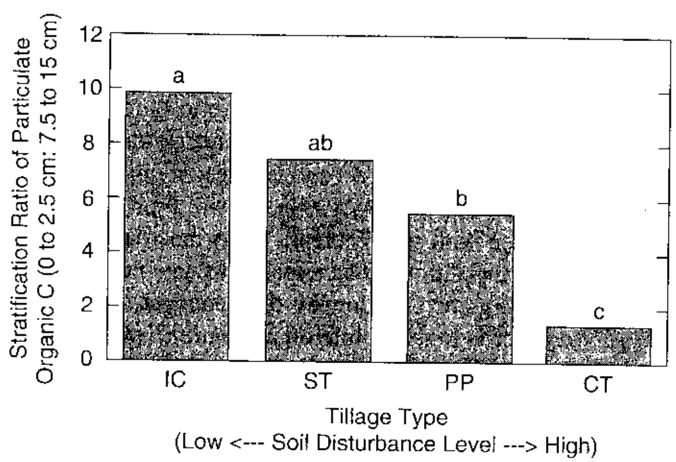


**FIGURE 8.12** Stratification ratio of particulate organic C at the end of 4 years under four tillage systems in the Georgia Piedmont. IC, in-row chisel at planting; ST, shallow tillage with sweeps during the growing season; PP, paraplow following harvest; and CT, conventional disk tillage. Bars labeled with different letters are significantly different at $p < 0.1$. (Data from Franzluebbers, A.J. 2002a. *Soil Tillage Res.* 66:95–106.)

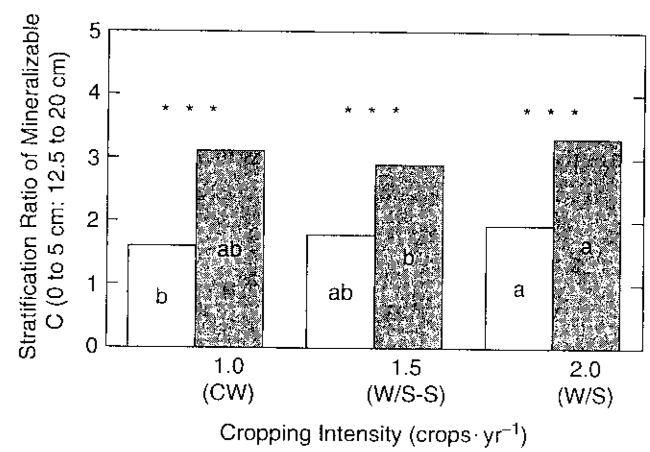


**FIGURE 8.13** Stratification ratio of mineralizable C at the end of 9 years under conventional (open bars) and no tillage (shaded bars) in three wheat rotation systems in southcentral Texas. CW, continuous wheat; W/S–S, wheat/soybean–sorghum; and W/S, continuous wheat/soybean double crop. *** indicates significance between tillage systems at $p < 0.001$. Within a tillage system, bars labeled with different letters are significantly different at $p < 0.1$. (Data from Franzluebbers, A.J. 2002a. *Soil Tillage Res.* 66:95–106.)

Stratification ratios of soil organic matter pools can be good indicators of soil quality, because surface soil properties are responsive to management, inherent levels of soil organic C are normalized in the calculation, and high stratification ratios are uncommon under degraded conditions (Franzluebbers, 2002a).

The effect of tillage/disturbance on soil organic matter is not equal among the components of organic matter. The following sections describe how tillage impacts total, particulate, and biologically active fractions of organic C and N.

## Aggregate-Size Distribution of Organic Matter

Organic matter is not only stratified with depth but can also be stratified three-dimensionally according to soil aggregation. Soil disturbance results in a more uniform distribution of organic substrates within soil (Figure 8.14). Lack of soil disturbance leads to concentration of organic matter within soil macroaggregates, which protect and isolate soil organic matter from consumption by soil fauna and microorganisms (Beare et al., 1994a, 1994b; Franzluebbers and Arshad, 1997b; Six et al., 2000c). Soil disturbance with tillage breaks apart macroaggregates and allows organic matter, once protected from decomposition, to be exposed to new environments and communities of organisms. Mineralization of organic C following disruption of soil macroaggregates is rapid, suggesting that this organic matter is highly labile on exposure (Figure 8.15).

A hierarchical approach to aggregate formation has been theorized, such that macroaggregates (>0.25 mm) form as a result of root entanglement and polysaccharides produced by heterotrophic microorganisms decomposing particulate organic matter glue together microaggregates (0.05 to 0.25 mm; Tisdall and Oades, 1982). A compilation of studies from the literature report that water-stable macroaggregation of surface soil is higher under no-tillage compared with inversion-tillage systems (Table 8.4). Available data suggests that macroaggregates under no tillage have a slower turnover time than under conventional tillage because of less physical perturbation, resulting in macroaggregates under no tillage that are enriched in fine particulate organic matter, which is more resistant to decomposition (Six et al., 2000b).

No tillage often leads to an improvement in soil structure because of reduced mechanical disturbance and greater reliance on soil organisms that deposit enriched organic debris along permanent soil pores. However, the depth to which changes in soil aggregation occurs might be limited, at least in the first decade. From a set of four soils in northern Alberta and British Columbia, the fraction of soil as water-stable macroaggregates (>0.25 mm) was higher under no tillage than under conventional tillage to a depth of 12.5 cm, but not below this depth (Figure 8.16). Enrichment

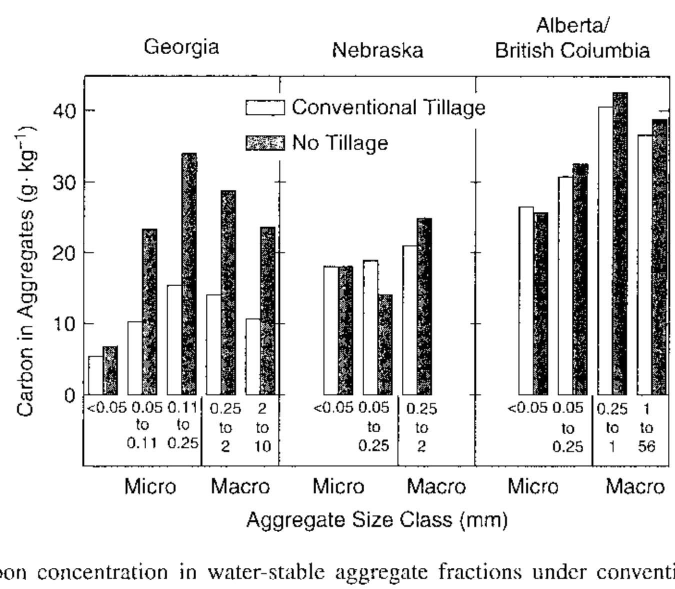


**FIGURE 8.14** Carbon concentration in water-stable aggregate fractions under conventional tillage and no tillage from Georgia, Nebraska, and Alberta/British Columbia, Canada. In general, soil organic C becomes enriched in macroaggregates (>0.25 mm) under no tillage. (Data for Georgia from Beare, M.H. et al. 1994b. *Soil Sci. Soc. Am. J.* 58:777–786; for Nebraska from Cambardella, C.A., and Elliott, E.T. 1993. *Soil Sci. Soc. Am. J.* 57:1071–1076; and for Alberta/British Columbia, Canada, from Franzluebbers, A.J., and Arshad, M.A., 1996c. *Can. J. Soil Sci.* 76:387–393.)

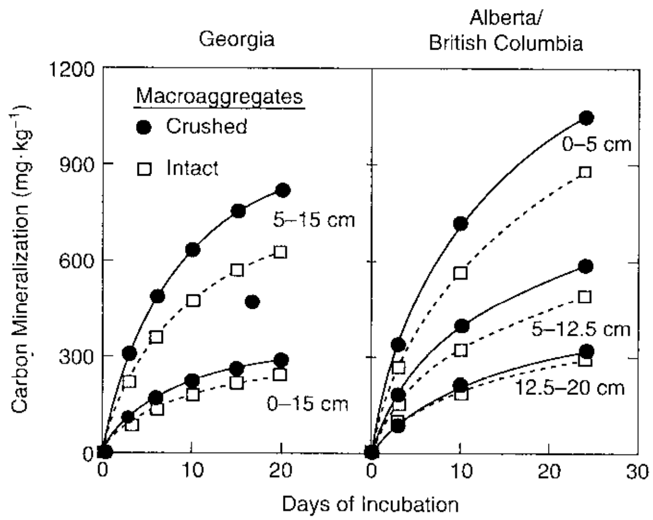


**FIGURE 8.15** Carbon mineralization during incubation of intact and crushed macroaggregates (>0.25 mm) from different soil depths in Georgia and in Alberta/British Columbia, Canada. Labile C protected within macroaggregates declines with soil depth. (Data for Georgia from Beare, M.H. et al. 1994b. *Soil Sci. Soc. Am. J.* 58:777–786; and for Alberta/British Columbia, Canada, from Franzluebbers, A.J., and Arshad, M.A. 1996c. *Can. J. Soil Sci.* 76:387–393.)

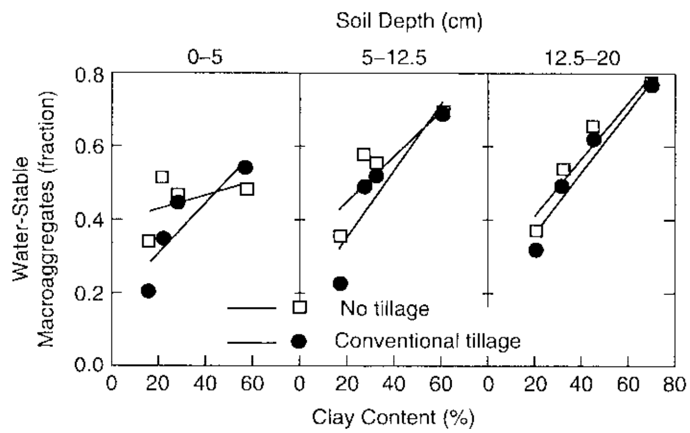


**FIGURE 8.16** Water-stable macroaggregates from three soil depths in four soils varying in soil texture under conventional and no tillage in Alberta/British Columbia, Canada. The positive effect of no tillage on macroaggregation was highest in coarse-textured soils and diminished with soil depth. (Data from Franzluebbers, A.J., and Arshad, M.A. 1996c. *Can. J. Soil Sci.* 76:387–393.)

of the soil surface with crop residues under no tillage led to significantly greater macroaggregation, especially in soils with coarse texture because their level of macroaggregation was lower than that in soils with fine texture. Fine-textured soils have a higher inherent level of macroaggregation even with soil disturbance because of the cohesive nature of highly reactive clays. This higher inherent level of aggregation can prevent further improvement with adoption of conservation tillage.

**TABLE 8.4**
**Comparison of Percent Water-Stable Macroaggregation among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Rhodic Kanhapludult | SCL | Georgia | 13 | 5 | — | 63 | — | 83 | Beare et al. (1994b) |
| Pachic Haplustoll | L | Nebraska | 20 | 20 | 23 | 29 | — | 39 | Cambardella and Elliott (1993) |
| Typic Cryoboralf | L | BC, Canada | 7 | 5 | — | 21 | — | 34 | Franzluebbers and Arshad (1997a) |
| Typic Cryoboralf | SiL | BC, Canada | 16 | 5 | — | 34 | — | 51 | Franzluebbers and Arshad (1997a) |
| Mollic Cryoboralf | CL | AB, Canada | 4 | 5 | — | 45 | — | 46 | Franzluebbers and Arshad (1997a) |
| Typic Natriboralf | C | AB, Canada | 6 | 5 | — | 54 | — | 48 | Franzluebbers and Arshad (1997a) |
| Typic Kanhapludult | SL | Georgia | 4 | 2.5 | — | 69 | — | 79 | Franzluebbers et al. (1999) |
| Pachic Haplustoll | L | Nebraska | 27 | 5 | 14 | — | — | 30 | Six et al. (2000a) |
| Typic Fragiudalf | SiL | Ohio | 34 | 5 | 15 | — | — | 56 | Six et al. (2000a) |
| Typic Hapludalf | SL | Michigan | 10 | 5 | 43 | — | — | 56 | Six et al. (2000a) |
| Typic Paleudalf | SiCL | Kentucky | 25 | 5 | 47 | — | — | 73 | Six et al. (2000a) |
| Vertisol | C | Qld, Australia | 8 | 10 | — | 25 | — | 32 | Hamblin (1980) |
| Alfisol | SL | NSW, Australia | 7 | 10 | — | 22 | — | 25 | Hamblin (1980) |
| Entisol | SL | WA, Australia | 5 | 10 | — | 9 | — | 17 | Hamblin (1980) |
| Spodosol | SL | Vic, Australia | 3 | 10 | — | 11 | — | 14 | Hamblin (1980) |
| Alfisol | SL | SA, Australia | 3 | 10 | — | 13 | — | 15 | Hamblin (1980) |
| Plow vs. no tillage ($Pr > F = 0.01$) | | | | | 28 | — | — | 51 | $n = 5$ |
| Shallow vs. no tillage ($Pr > F = 0.01$) | | | | | — | 33 | — | 40 | $n = 12$ |

## Total Organic C and N

Numerous reports are now available comparing the effect of conservation tillage with conventional inversion tillage on soil organic C and N. Although estimates of soil organic C and N were not always available at the initiation of long-term studies, relative changes in soil organic C and N between tillage systems can provide useful information on the fate of organic matter. Soil organic C in the Ap horizon (0- to 20-cm depth) of a Dark Brown Chernozemic clay loam in Alberta increased at 0.17 to 0.20 mg $g^{-1}$ soil $year^{-1}$ in two studies conducted for 9 and 19 years under no tillage compared with shallow disk tillage (Dormaar and Lindwall, 1989). In contrast, soil organic C at a depth of 0 to 7.5 cm during 4 years under no tillage compared with plowing increased at 0.69 mg $g^{-1}$ soil $year^{-1}$ on a Waukegon silt loam in Minnesota (Hansmeyer et al., 1997) and at ~1.15 mg $g^{-1}$ soil $year^{-1}$ on a Kamouraska clay in Quebec (Angers et al., 1993a). Incorporation of residues below 7.5 cm with plowing would likely reduce this effect when considering the entire plow depth. Soil organic C accumulation rates between these extremes have also been observed. At a depth of 0 to 5 cm, soil organic C increased at 0.42 mg $g^{-1}$ soil $year^{-1}$ during 14 years under no tillage compared with multiple-disk tillage on a Norfolk loamy sand in the South Carolina Coastal Plain (Hunt et al., 1996) and at 0.28 to 0.42 mg $g^{-1}$ soil $year^{-1}$ during more than 20 years under no tillage compared with plowing on a Bertie silt loam in the Maryland Coastal Plain (McCarty and Meisinger, 1997). On a Hoytville silty clay loam in Ohio, soil organic C of the 0- to 10-cm depth increased at 0.66 mg $g^{-1}$ soil $year^{-1}$ during 12 years under no tillage compared with plowing (Lal et al., 1990). The large range of changes in soil organic C with no tillage compared with inversion tillage among the aforementioned studies can be related to differences in cropping system, fertilization, depth of tillage tool, numerous soil characteristics, climatic conditions, and depth of sampling.

In general, compilation studies looking at the effect of conservation tillage on soil organic matter indicate that soil under long-term no tillage accumulates organic C to a greater extent than under inversion tillage (Kern and Johnson, 1991; Rasmussen and Collins, 1991; Reicosky et al., 1995; Paustian et al., 1997; Lal et al., 1998). The magnitude of difference between no tillage and conventional tillage can be as high as 2 kg $m^{-2}$ (Dick et al., 1998), but more typical differences center around 30 g $m^{-2}$ $year^{-1}$ (Figure 8.17). There are a number of cases where the total stock of soil organic C and N in the upper 20 to 30 cm does not change with adoption of conservation tillage compared with conventional tillage (Carter and Rennie, 1982; Franzluebbers and Arshad, 1996c; Angers et al., 1997; Wander et al., 1998). Although the C and N content in surface residues are not always accounted in agricultural systems, this trash component at the soil surface can be significant (Figure 8.10).

Climatic factors, such as precipitation and temperature, appear to exert a great deal of control on the potential of conservation-tillage systems to sequester more soil organic C compared with conventional-tillage systems (Franzluebbers and Steiner, 2002). Potential soil organic C storage with no tillage compared with conventional tillage in North America was highest (~58 g $m^{-2}$ $year^{-1}$) in mesic, subhumid regions with mean annual precipitation-to-potential evapotranspiration ratios of 1.4 to 1.6 mm $mm^{-1}$ (Figure 8.18). Tillage comparisons in more extreme climates have often produced estimates of potential soil organic C storage with no tillage that are no different or less than those from under conventional tillage. For example, in the cold, semiarid climate in northern Alberta, soil organic C was not different between tillage systems in three of four soils (Franzluebbers and Arshad, 1996b). No tillage generally conserves surface soil moisture compared with conventional tillage. Shallow tillage in this semiarid environment incorporates residues near the soil surface, which dries frequently and more rapidly than under no tillage. Because soil is frozen for nearly 5 months of the year, with the remaining time devoted to crop production and utilization of available water, there are limited opportunities for decomposition to occur under either tillage system, resulting in little change in potential soil organic C storage with tillage.

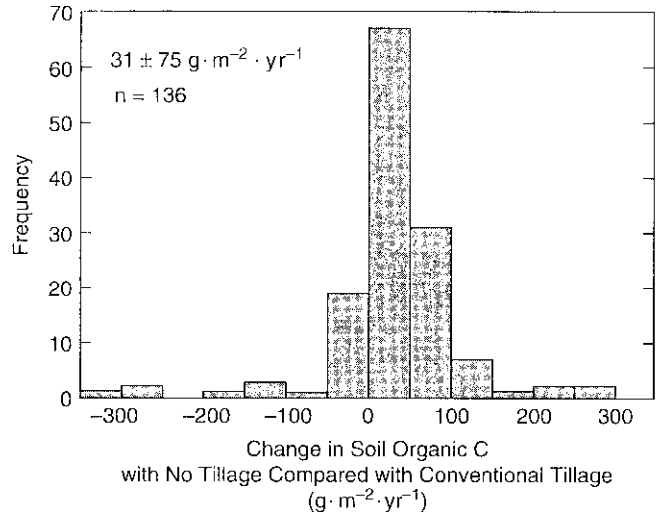


**FIGURE 8.17** Frequency distribution of 136 observations from North America on the change in soil organic C with no tillage compared with conventional tillage. Rate in upper left corner is mean and standard deviation from 136 observations. (Updated from Franzluebbers, A.J., and Steiner, J.L. 2002. In Kimble, J.M., Lal, R., and Follett, R.F. (Eds.), *Agriculture Practices and Policies for Carbon Sequestration in Soil*. CRC Press, Boca Raton, FL, pp. 71–86, with data compiled from Angers, D.A. et al. 1997. *Soil Tillage Res.* 41:191–201; Angers, D.A. et al. 1994. In *Proceedings of the 13th International Soil Tillage Research Organization*, Denmark, pp. 49–54; Beare, M.H. et al. 1994b. *Soil Sci. Soc. Am. J.* 58:777–786; Black, A.L., and Tanaka, D.L. 1997. In Paul, E.A., Paustian, K., Elliott, E.T., and Cole, C.V. (Eds.), *Soil Organic Matter in Temperate Agroecosystems*. CRC Press, Boca Raton, FL, pp. 335–342; Blevins, R.L. et al. 1977. *Agron. J.* 69:383–386; Cambardella, C.A., and Elliott, E.T. 1992. *Soil Sci. Soc. Am. J.* 56:777–783; Campbell, C.A. et al. 1995. *Can. J. Soil Sci.* 75:449–458; Campbell, C.A. et al. 1996. *Soil Tillage Res.* 37:3–14; Carter, M.R., and Rennie, D.A. 1982. *Can. J. Soil Sci.* 62:587–597; Carter, M.R. et al. 1988. *Soil Tillage Res.* 12:365–384; Carter, M.R. et al. 2002. *Soil Tillage Res.* 67:85–98; Clapp, C.E. et al. 2000. *Soil Tillage Res.* 55:127–142; Dick, W.A. et al. 1998. *Soil Tillage Res.* 47:235–244; Duiker, S.W., and Lal, R. 1999. *Soil Tillage Res.* 52:73–81; Edwards, J.H. et al. 1992. *Soil Sci. Soc. Am. J.* 56:1577–1582; Eghball, B. et al.1994. *J. Soil Water Conserv.* 49:201–205; Follett, R.F., and Peterson, G.A. 1988. *Soil Sci. Soc. Am. J.* 52:141–147; Franzluebbers, A.J., and Arshad, M.A. 1996c. *Can. J. Soil Sci.* 76:387–393; Franzluebbers, A.J. et al. 1994a. *Soil Sci. Soc. Am. J.* 58:1639–1645; Franzluebbers, A.J. et al. 1995b. *Soil Sci. Soc. Am. J.* 59:460–466; Franzluebbers, A.J. et al. 1998. *Soil Tillage Res.* 47:303–308; Franzluebbers, A.J. et al. 1999. *Soil Sci. Soc. Am. J.* 63:349–355; Halvorson, A.D. et al. 1997. In Paul, E.A., Paustian, K., Elliott, E.T., and Cole, C.V. (Eds.), *Soil Organic Matter in Temperate Agroecosystems*. CRC Press, Boca Raton, FL, pp. 361–370; Hendrix, P.F. et al. 1998. *Soil Tillage Res.* 47:245–251; Ismail, I. et al. *Soil Sci. Soc. Am. J.* 58:193–198; Karlen, D.L. et al. 1998. *Soil Tillage Res.* 48:155–165; Karlen, D.L. et al. 1994. *Soil Tillage Res.* 32:313–327; Lal, R. et al. 1994. *Soil Sci. Soc. Am. J.* 58:517–522; Lamb, J.A. et al. 1985. *Soil Sci. Soc. Am. J.* 49:352–356; Larney, F.J. et al. 1997. *Soil Tillage Res.* 42:229–240; McCarty, G.W. et al. 1998. *Soil Sci. Soc. Am. J.* 62:1564–1571; Mielke, L.N. et al. 1986. *Soil Tillage Res.* 5:355–366; Nyborg, M. et al. 1995. In Lal, R., Kimble, J., Levine, E., and Stewart, B.A. (Eds.), *Soil Management and Greenhouse Effect*. Lewis Publishers, CRC Press, Boca Raton, FL, pp. 93–99; Peterson, G.A. et al. 1998. *Soil Tillage Res.* 47:207–218; Pierce, F.J. et al. 1994. *Soil Sci. Soc. Am. J.* 58:1782–1787; Pikul, J.L., Jr., and Aase, J.K. 1995. *Agron. J.* 87:656–662; Potter, K.N. et al. 1997. *Soil Sci.* 162:140–147; Potter, K.N. et al. 1998. *Soil Tillage Res.* 47:309–321; Rhoton, F.E. et al. 2002. *Soil Tillage Res.* 66:1–11; Sainju, U.M. et al. 2002. *Soil Tillage Res.* 63:167–179; Salinas-Garcia, J.R. et al. 1997b. *Soil Tillage Res.* 42:79–93; Schomberg, H.H., and Jones, O.R. 1999. *Soil Sci. Soc. Am. J.* 63:1359–1366; Six, J. et al. 2000c. *Soil Sci. Soc. Am. J.* 64:681–689; Wander, M.M. et al. 1998. *Soil Sci. Soc. Am. J.* 62:1704–1711; Wanniarachchi, S.D. et al. A.F. 1999. *Can. J. Soil Sci.* 79:473–480; Yang, X.M., and Wander, M.M. 1999. *Soil Tillage Res.* 52:1–9; and Yang, X.M., and Kay, B.D. 2001. *Soil Tillage Res.* 59:107–114.)

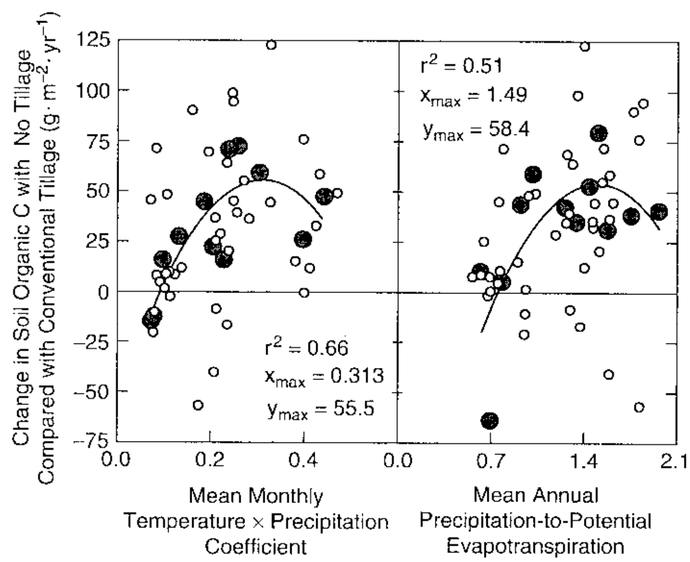


**FIGURE 8.18** Change in soil organic C with no tillage compared with conventional tillage in North America as a function of macroclimatic indices. Mean monthly temperature × precipitation coefficient was composed of a temperature coefficient (0 to 1; logarithmic relationship with maximum at 30°C) and a precipitation coefficient (0 to 1; linear-plateau relationship with maximum at 100 mm month$^{-1}$). Potential evapotranspiration was calculated by the Thornthwaite procedure. Small circles represent individual sites and large circles represent means of four consecutive sites in ranked climatic order. Regression parameters are based on means. (Updated from Franzluebbers, A.J., and Steiner, J.L. 2002. In Kimble, J.M., Lal, R., and Follett, R.F., Eds., *Agriculture Practices and Policies for Carbon Sequestration in Soil*. CRC Press, Boca Raton, FL, pp. 71–86. With permission.)

According to several published reports, the effect of tillage management on soil organic N content in the rooting zone suggests that no tillage leads to significantly higher soil organic N content than either plow or shallow tillage do (Table 8.5). Calculated on a yearly basis, soil organic N was 2.3 ± 6.7 g m$^{-2}$ year$^{-1}$ higher under no tillage than under plow tillage ($n$ = 24). Soil organic N storage with no tillage compared with shallow tillage was 2.8 ± 7.0 g m$^{-2}$ year$^{-1}$ ($n$ = 26). Although the mean change with adoption of no tillage compared with conventional tillage was positive among these studies, there was a great deal of variation. This variation suggests that much more work is needed to understand the mechanisms behind these differences. Detailed temporal analyses within several long-term studies would help separate random sampling variation from biogeochemical controls, including climate, mineralogy, soil texture, cropping system, and fertilization regime.

## Particulate Fraction of Organic Matter

Particulate organic matter is defined as that portion of organic matter retained on a 50-μm screen following complete dispersion of soil. Particulate organic matter is considered to represent the slow pool of organic matter (Cambardella and Elliott, 1992), with an intermediate turnover time between the active and passive pools of organic matter (Parton et al., 1987). Particulate organic matter is derived from above- and belowground inputs of plant residues. Particulate organic C is often greater near the soil surface than at lower depths because of the dominant input from crop residues (Figure 8.19). Surface residue retention with no tillage can lead to higher particulate organic C near the soil surface than with inversion tillage systems (Figure 8.19). According to a compilation of studies in the literature, particulate organic C under no tillage is greater than under either plow or shallow tillage (Table 8.6). The effect of tillage system on particulate organic N content in the surface 15

**TABLE 8.5**
**Comparison of Total Soil N (g m$^{-2}$) among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Haplorthod | fSL | PEI, Canada | 8 | 60 | 688 | — | — | 607 | Angers et al. (1997) |
| Cryoboralf | L | PEI, Canada | 8 | 60 | 366 | 359 | — | — | Angers et al. (1997) |
| Humaquept | C | QC, Canada | 6 | 60 | 756 | — | — | 675 | Angers et al. (1997) |
| Humaquept | CL | QC, Canada | 4 | 60 | 520 | 483 | — | — | Angers et al. (1997) |
| Humaquept | SiC | QC, Canada | 3 | 60 | 815 | 715 | — | 823 | Angers et al. (1997) |
| Eutrochrept | SL | ON, Canada | 5 | 60 | 592 | — | — | 568 | Angers et al. (1997) |
| Haplaquoll | CL | ON, Canada | 11 | 60 | 1008 | — | — | 974 | Angers et al. (1997) |
| Aeric Haplaquept | SiL | QC, Canada | 11 | 24 | 472 | 488 | 472 | — | Angers et al. (1993b) |
| Paleudult | SCL | Brazil | 9 | 30 | 402 | — | — | 424 | Bayer et al. (2000b) |
| Rhodic Kanhapludult | SCL | Georgia | 13 | 15 | — | 235 | — | 259 | Beare et al. (1994b) |
| Typic Argiboroll | SiL | North Dakota | 6 | 30 | 570 | 566 | — | 565 | Black and Tanaka (1997) |
| Pachic Haplustoll | L | Nebraska | 20 | 20. | — | 325 | — | 326 | Cambardella and Elliott (1992) |
| Typic Haploboroll | SiL | SK, Canada | 4 | 15 | — | 304 | — | 313 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 8 | 15 | — | 308 | — | 314 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 12 | 15 | — | 298 | — | 312 | Campbell et al. (1999) |
| Typic Haploboroll | fSL | SK, Canada | 3 | 15 | — | 209 | — | 214 | Campbell et al. (1996) |
| Typic Haploboroll | fSL | SK, Canada | 7 | 15 | — | 187 | — | 194 | Campbell et al. (1996) |
| Typic Haploboroll | fSL | SK, Canada | 11 | 15 | — | 218 | — | 226 | Campbell et al. (1996) |
| Udic Pellustert | C | Qld, Australia | 13 | 30 | | 429 | — | 461 | Dalal (1989) |
| Udic Pellustert | C | Qld, Australia | 20 | 10 | | 141 | — | 141 | Dalal et al. (1991) |
| Typic Paleudalf | SiL | Kentucky | 11 | 15 | 377 | — | — | 479 | Doran (1987) |
| Aeric Ochraqualf | SiL | Illinois | 6 | 15 | 303 | — | — | 358 | Doran (1987) |
| Aquic Hapludoll | CL | Minnesota | 6 | 15 | 622 | — | — | 631 | Doran (1987) |
| Pachic Argiustoll | SiCL | Nebraska | 6 | 15 | 338 | — | — | 462 | Doran (1987) |
| Pachic Haplustoll | L | Nebraska | 13 | 15 | 259 | 277 | — | 296 | Doran (1987) |
| Aridic Argiustoll | SiL | Nebraska | 12 | 15 | 369 | 387 | — | 370 | Doran (1987) |
| Fluventic Ustochrept | SiCL | Texas | 9 | 20 | — | 258 | — | 333 | Franzluebbers et al. (1994a) |
| Typic Kanhapludult | SL | Georgia | 4 | 15 | — | 159 | — | 155 | Franzluebbers et al. (1999) |
| Aridic Paleustoll | SiL | Colorado | 15 | 20 | — | 216 | — | 223 | Halvorson et al. (1997) |

| Soil Type | Texture | Location | Years | Depth (cm) | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Typic Paleudalf | SiL | Kentucky | 20 | 30 | 621 | — | — | 645 | Ismail et al. (1994) |
| Typic Hapludalf | SiL | Wisconsin | 25 | 12 | 535 | 625 | — | 727 | Karlen et al. (1994) |
| Typic Haploboroll | SCL | AB, Canada | 16 | 15 | — | 298 | — | 303 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 8 | 15 | — | 325 | — | 343 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 9 | 15 | — | 374 | — | 376 | Larney et al. (1997) |
| Typic Hapludalf | SiL | Germany | 9 | 30 | 426 | 442 | — | — | Meyer et al. (1996) |
| Vertic Calcixeroll | C | Morocco | 11 | 20 | — | 328 | — | 352 | Mrabet et al. (2001) |
| Typic Cryoboralf | L | AB, Canada | 11 | 15 | — | 276 | — | 326 | Nyborg et al. (1995) |
| Typic Cryoboralf | L | AB, Canada | 11 | 15 | — | 776 | — | 785 | Nyborg et al. (1995) |
| Aeric Ochraqualf | L | Michigan | 11 | 20 | 333 | — | — | 379 | Pierce et al. (1994) |
| Typic Ochraqualf | SCL | Texas | 16 | 20 | 134 | 158 | — | 200 | Salinas-Garcia et al. (1997b) |
| Torrertic Paleustoll | CL | Texas | 8 | 12 | — | 88 | — | 98 | Schomberg and Jones (1999) |
| Pachic Haplustoll | L | Nebraska | 27 | 20 | 312 | — | — | 366 | Six et al. (2000c) |
| Typic Fragiudalf | SiL | Ohio | 34 | 20 | 294 | — | — | 346 | Six et al. (2000c) |
| Typic Hapludalf | SL | Michigan | 10 | 20 | 204 | — | — | 218 | Six et al. (2000c) |
| Typic Paleudalf | SiCL | Kentucky | 25 | 20 | 348 | — | — | 441 | Six et al. (2000c) |
| Typic Hapludalf | SiL | Germany | 20 | 30 | 480 | 490 | — | — | Stockfisch et al. (1999) |
| Aquic Argiudoll | SiL | Illinois | 10 | 30 | 466 | — | — | 532 | Wander et al. (1998) |
| Aquic Hapludoll | SiL | Illinois | 10 | 30 | 844 | — | — | 835 | Wander et al. (1998) |
| Typic Haplaquoll | SiCL | Illinois | 10 | 30 | 997 | — | — | 1066 | Wander et al. (1998) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15 | 423 | — | — | 442 | Wander and Bollero (1999) |
| | | | | | | | | | |
| Plow vs. shallow tillage (Pr > F = 0.78) | | | | | 450 | 454 | — | — | $n = 11$ |
| Plow vs. no tillage (Pr > F = 0.01) | | | | | 504 | — | — | 537 | $n = 25$ |
| Shallow vs. no tillage (Pr > F < 0.01) | | | | | — | 326 | — | 348 | $n = 26$ |

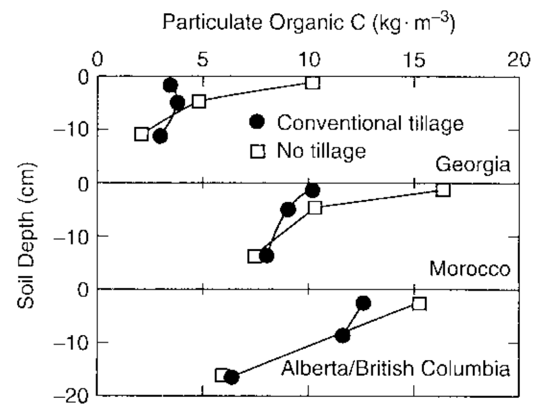


**FIGURE 8.19** Depth distribution of particulate organic C under conventional and no tillage in Georgia, near Settat Morocco, and in Alberta/British Columbia, Canada. (Data for Georgia from Franzluebbers, A.J. et al. 1999. *Soil Sci. Soc. Am. J.* 63:349–355; for Settat Morocco from Mrabet, R. et al. 2001. *Soil Tillage Res.* 57:225–235; and for Alberta/British Columbia, Canada from Franzluebbers, A.J., and Arshad, M.A. 1997a. *Soil Sci. Soc. Am. J.* 61:1382–1386.)

to 30 cm is less clear (Table 8.7). Paired *t*-tests of the effects of no tillage compared with other tillage systems on particulate organic N were not significant, although the trend was for numerically higher values under no-tillage compared with inversion-tillage systems, similar to that found for particulate organic C.

The decomposability of particulate organic matter does not appear to be affected by tillage management. In a set of four Cryoboralfs and Natriboralfs from Alberta and British Columbia, specific mineralization of particulate organic C was similar between shallow tillage and no tillage (Franzluebbers and Arshad, 1997a). However, the ratio of specific particulate organic C mineralization to specific whole-soil organic C mineralization was higher under no tillage (1.3) than under shallow tillage (1.0), suggesting that particulate organic C was of better quality (i.e., more mineralizable) under no tillage relative to other pools of soil organic C. Mineralizable whole-soil C under no tillage was significantly lower than under shallow tillage in two of the four soils (Franzluebbers and Arshad, 1996a, 1996b).

## Density Fractions of Organic Matter

Soil organic matter can be separated by density to distinguish fractions along a decomposition gradient. Lightest fractions of organic matter represent recently deposited organic residues. Heaviest fractions of organic matter represent highly decomposed organic residues that become associated with mineral particles. Separation of light fractions from heavy fractions is typically in an unreactive salt solution with a density of 1.6 to 1.8 Mg $m^{-3}$. Light fractions float to the surface, whereas heavy fractions sink with sediment. Tillage effects on density fractions of organic matter have not been extensively investigated. Although not different between tillage systems to a depth of 20 cm, light-fraction C (<1.6 Mg $m^{-3}$) and medium-fraction C (1.6 to 2.0 Mg $m^{-3}$) were higher under no tillage than under plow tillage at a depth of 0–5 cm in a Typic Argiudoll in Argentina, but lower at a depth of 5–15 cm (Alvarez et al., 1998). Heavy-fraction C was unaffected by tillage management at all soil depths. In the surface 15 cm of Typic Haploborolls in Alberta, light-fraction C under no tillage for 8 to 16 years averaged 242 g $m^{-2}$ and 226 g $m^{-2}$ under shallow tillage (Larney et al., 1997). At a depth of 0 to 15 cm, light-fraction C was lower under no tillage than under blade cultivation in Alberta (Dormaar and Lindwall, 1989). At the end of 5 years on a Udic Dystrochrept in New Zealand, light-fraction C was not different at a depth of 0 to 5 cm under ryegrass that was either plowed or direct drilled annually (Haynes, 1999). Light-fraction C content to a depth of 20 cm was not statistically different in a Pachic Haplustoll under plow tillage (174 g $m^{-2}$) and no tillage (196 g $m^{-2}$) for 27 years (Six et al., 1998).

**TABLE 8.6**
**Comparison of Particulate Organic C (kg m$^{-2}$) among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Aeric Haplaquept | SiL | QC, Canada | 10 | 24 | 0.56 | 0.84 | 0.99 | — | Angers et al. (1994) |
| Aeric Haplaquept | SiL | QC, Canada | 11 | 8 | 0.38 | 0.46 | 0.43 | — | Angers et al. (1995) |
| Rhodic Kanhapludult | SCL | Georgia | 13 | 15 | — | 1.00 | — | 1.24 | Beare et al. (1994b) |
| Pachic Haplustoll | L | Nebraska | 20 | 20 | 0.56 | 0.68 | — | 0.93 | Cambardella and Elliott (1992) |
| Typic Cryoboralf | L | BC, Canada | 7 | 20 | — | 1.78 | — | 1.71 | Franzluebbers and Arshad (1997a) |
| Typic Cryoboralf | SiL | BC, Canada | 16 | 20 | — | 2.28 | — | 2.20 | Franzluebbers and Arshad (1997a) |
| Mollic Cryoboralf | CL | AB, Canada | 4 | 20 | — | 2.54 | — | 2.80 | Franzluebbers and Arshad (1997a) |
| Typic Natriboralf | C | AB, Canada | 6 | 20 | — | 1.29 | — | 1.58 | Franzluebbers and Arshad (1997a) |
| Typic Kanhapludult | SL | Georgia | 4 | 15 | — | 0.51 | — | 0.65 | Franzluebbers et al. (1999) |
| Typic Arigiboroll | SiL | North Dakota | 12 | 20[a] | — | 0.43 | — | 0.36 | Frey et al. (1999) |
| Pachic Haplustoll | L | Nebraska | 26 | 20[a] | 0.35 | — | — | 0.48 | Frey et al. (1999) |
| Aridic Argiustoll | L | Colorado | 11 | 20[a] | — | 0.38 | — | 0.30 | Frey et al. (1999) |
| Torrertic Paleustoll | CL | Texas | 15 | 20[a] | — | 0.18 | — | 0.16 | Frey et al. (1999) |
| Cumulic Haplustoll | SiL | Kansas | 22 | 20[a] | — | 0.36 | — | 0.41 | Frey et al. (1999) |
| Typic Paleudalf | SiCL | Kentucky | 26 | 20[a] | 0.44 | — | — | 0.52 | Frey et al. (1999) |
| Oxyaquic Fragiudalf | SiL | Illinois | 8 | 15[a] | 0.69 | 0.75 | — | 0.83 | Hussain et al. (1999) |
| Vertic Calcixeroll | C | Morocco | 11 | 20 | — | 1.70 | — | 1.84 | Mrabet et al. (2001) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15[a] | 0.62 | — | — | 0.59 | Needelman et al. (1999) |
| Pachic Haplustoll | L | Nebraska | 27 | 20 | 0.37 | — | — | 0.53 | Six et al. (1999) |
| Typic Hapludalf | SL | Michigan | 10 | 20 | 0.47 | — | — | 0.45 | Six et al. (1999) |
| Typic Fragiudalf | SiL | Ohio | 34 | 20 | 0.52 | — | — | 0.79 | Six et al. (1999) |
| Typic Paleudalf | SiCL | Kentucky | 25 | 20 | 0.42 | — | — | 0.55 | Six et al. (1999) |
| Aquic Argiudoll | SiL | Illinois | 10 | 30 | 0.66 | — | — | 0.71 | Wander et al. (1998) |
| Aquic Hapludoll | SiL | Illinois | 10 | 30 | 1.21 | — | — | 1.45 | Wander et al. (1998) |
| Typic Haplaquoll | SiCL | Illinois | 10 | 30 | 2.61 | — | — | 2.44 | Wander et al. (1998) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15[b] | 0.70 | — | — | 0.73 | Wander and Bollero (1999) |
| Plow vs. shallow tillage ($Pr > F = 0.07$) | | | | | 0.55 | 0.68 | — | — | $n = 4$ |
| Plow vs. ridge tillage ($Pr > F = 0.43$) | | | | | 0.47 | — | 0.71 | — | $n = 2$ |
| Plow vs. no tillage ($Pr > F = 0.02$) | | | | | 0.74 | — | — | 0.85 | $n = 13$ |
| Shallow vs. no tillage ($Pr > F = 0.05$) | | | | | — | 1.07 | — | 1.15 | $n = 13$ |

[a] Assumed a bulk density of 1.2 Mg m$^{-3}$ for soil at a depth of 0–5 cm and 1.4 Mg m$^{-3}$ for soil at a depth of either 5–15 or 5–20 cm.

[b] Assumed a bulk density of 1.33 Mg m$^{-3}$ for soil at a depth of 0–15 cm.

**TABLE 8.7**
**Comparison of Particulate Organic N (g $m^{-2}$) among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Rhodic Kanhapludult | SCL | Georgia | 13 | 15 | — | 75 | — | 99 | Beare et al. (1994b) |
| Pachic Haplustoll | L | Nebraska | 20 | 20 | 48 | 53 | — | 40 | Cambardella and Elliott (1992) |
| Typic Arigiboroll | SiL | North Dakota | 12 | 20[a] | — | 28 | — | 28 | Frey et al. (1999) |
| Pachic Haplustoll | L | Nebraska | 26 | 20[a] | 28 | — | — | 48 | Frey et al. (1999) |
| Aridic Argiustoll | L | Colorado | 11 | 20[a] | — | 26 | — | 22 | Frey et al. (1999) |
| Torrertic Paleustoll | CL | Texas | 15 | 20[a] | — | 14 | — | 14 | Frey et al. (1999) |
| Cumulic Haplustoll | SiL | Kansas | 22 | 20[a] | — | 27 | — | 32 | Frey et al. (1999) |
| Oxyaquic Fragiudalf | SiL | Illinois | 8 | 15[a] | 50 | 56 | — | 65 | Hussain et al. (1999) |
| Typic Paleudalf | SiCL | Kentucky | 26 | 20[a] | 33 | — | — | 36 | Frey et al. (1999) |
| Aquic Argiudoll | SiL | Illinois | 10 | 30 | 57 | — | — | 65 | Wander et al. (1998) |
| Aquic Hapludoll | SiL | Illinois | 10 | 30 | 94 | — | — | 123 | Wander et al. (1998) |
| Typic Haplaquoll | SiCL | Illinois | 10 | 30 | 235 | — | — | 217 | Wander et al. (1998) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15[b] | 46 | — | — | 52 | Wander and Bollero (1999) |
| Plow vs. shallow tillage (Pr > F = 0.06) | | | | | 49 | 55 | — | — | $n = 2$ |
| Plow vs. no tillage (Pr > F = 0.24) | | | | | 74 | — | — | 81 | $n = 8$ |
| Shallow vs. no tillage (Pr > F = 0.52) | | | | | — | 40 | — | 43 | $n = 7$ |

[a] Assumed a bulk density of 1.2 Mg $m^{-3}$ for soil at a depth of 0–5 cm and 1.4 Mg $m^{-3}$ for soil at a depth of either 5–15 or 5–20 cm.

[b] Assumed a bulk density of 1.33 Mg $m^{-3}$ for soil at a depth of 0–15 cm.

## Biologically Active Fractions of Organic Matter

Biologically active fractions of soil organic matter are important in assessing nutrient cycling, decomposition potential, and biophysical manipulation of soil structure. Biologically active fractions of soil organic matter include microbial biomass, readily mineralizable C and N, and some chemical indices of labile organic substrates. All these fractions have a relatively short turnover time and would be part of the active pool of the active–slow–passive soil organic matter continuum (Parton et al., 1987). According to a compilation of studies from the literature, mineralizable C and N were generally higher under no-tillage than under inversion-tillage systems (Table 8.8 and Table 8.9). As with other pools of organic matter, differences in mineralizable C between tillage systems tend to be greatest nearest the soil surface (Figure 8.8). Data in Table 8.8 were compiled from the uppermost sampling depth reported and are therefore not necessarily representative of results that might occur summed to the surface 20 to 30 cm of soil. Mineralizable C represents potential activity under optimum temperature and moisture conditions. As such, it represents the lack of *in situ* mineralization that might occur in the field. Inversion tillage that stimulates microbial activity in the field leads to an exhaustion of substrates that contribute to this mineralizable C pool.

Lack of C input to feed the heterotrophic community of soil organisms will lead to a reduction in biologically active soil organic matter pools. When sorghum residues were removed for 6 years from an Entic Pellustert in Australia, mineralizable C of the surface 10 cm of soil declined by an average of 29% (Saffigna et al., 1989). Microbial biomass N in the surface 10 cm of soil was reduced by 16 ± 8% in an Udic Pellustert in Australia following 20 years of burning of wheat and barley residues compared with residue retention (Dalal et al., 1991). During the ninth and tenth years of a cropping system study on a Fluventic Ustochrept in Texas, mineralizable C increased linearly with additional C input from more intensive cropping systems under both conventional and no tillage (Figure 8.20). In this study, there was no evidence of an interaction between cropping intensity and tillage management on the response in mineralizable C, as slopes between tillage systems were essentially the same.

Seasonal differences in mineralizable C can occur as a result of pulses of C inputs from plant roots and aboveground residues. In a Fluventic Ustochrept in Texas, mineralizable C at wheat planting was 89% higher under no tillage than under conventional tillage at a depth of 0–5 cm, but 12% lower at a depth of 5–12.5 cm (Figure 8.21). At wheat flowering, mineralizable C increased in both tillage systems most notably toward the soil surface, but at all depths as a result of accumulation of roots and rhizodeposits, which provided readily decomposable substrates. Long-term tillage effects (i.e., 9 years) were maintained despite seasonal changes that occurred.

Seasonal changes in mineralizable N do not necessarily mirror seasonal changes in mineralizable C, because inputs of high levels of readily decomposable substrates can lead to net immobilization of N in the short term. In the long term, mineralizable C and N generally correspond more directly once steady-state levels of organic matter quality are reached. In a Fluventic Ustochrept in Texas, cyclical changes in mineralizable N were evident under both conventional and no tillage in a 2-year sorghum–wheat/soybean rotation (Figure 8.22). Differences in mineralizable N between tillage systems occurred during approximately half of the rotation sequence, i.e., primarily during the soybean to sorghum phases of the rotation. Mineralizable N was suppressed to equal levels under both tillage systems during the wheat phase, probably because of the high level of rhizodeposition that occurs with the dense, fibrous root system of wheat. Roots and rhizosphere products can be low in N concentration and high in mineralizable C, leading to significant N immobilization (Mary et al., 1993).

Accumulation of residues at the soil surface with conservation tillage systems provides a habitat for a variety of soil fauna, which have important implications on the cycling of organic matter into biologically active pools (Kladivko, 2001). The most visible effect of conservation

**TABLE 8.8**
**Comparison of Mineralizable C in Surface Soil among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Units | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Typic Argiudoll | SiL | Argentina | 15 | 5 | mg kg$^{-1}$ d$^{-1}$ | 14 | — | — | 51 | Alvarez et al. (1998) |
| Rhodic Kanhapludult | SCL | Georgia | 13 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 22 | — | 37 | Beare et al. (1994b) |
| Aridic Paleustoll | L | Colorado | 5 | 5 | kg ha$^{-1}$ d$^{-1}$ | — | 2.6 | — | 3.5 | Burke et al. (1995) |
| Ustollic Haplargid | SL | Colorado | 5 | 5 | kg ha$^{-1}$ d$^{-1}$ | — | 4.1 | — | 3.0 | Burke et al. (1995) |
| Typic Haploboroll | SiL | SK, Canada | 4 | 7.5 | kg ha$^{-1}$ d$^{-1}$ | — | 9.7 | — | 11.4 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 8 | 7.5 | kg ha$^{-1}$ d$^{-1}$ | — | 5.8 | — | 5.8 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 12 | 7.5 | kg ha$^{-1}$ d$^{-1}$ | — | 6.0 | — | 6.1 | Campbell et al. (1999) |
| Typic Haploboroll | L | SK, Canada | 6 | 7.5 | mg kg$^{-1}$ d$^{-1}$ | — | 12 | — | 21 | Campbell et al. (1989) |
| Typic Boroll | SiL | AB, Canada | 16 | 4 | mg kg$^{-1}$ d$^{-1}$ | — | 12 | — | 16 | Carter and Rennie (1984) |
| Udic Boroll | CL | SK, Canada | 12 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 15 | — | 20 | Carter and Rennie (1984) |
| Typic Boroll | CL | SK, Canada | 4 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 15 | — | 26 | Carter and Rennie (1984) |
| Typic Boroll | L | SK, Canada | 2 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 14 | — | 14 | Carter and Rennie (1984) |
| Typic Hapludalf | L | Michigan | 8 | 20 | mg kg$^{-1}$ d$^{-1}$ | 2.9 | — | — | 3.1 | Collins et al. (2000) |
| Mollic Ochraqualf | SiCL | Ohio | 30 | 20 | mg kg$^{-1}$ d$^{-1}$ | 4.0 | — | — | 7.9 | Collins et al. (2000) |
| Typic Fragiudalf | SiL | Ohio | 30 | 20 | mg kg$^{-1}$ d$^{-1}$ | 3.6 | — | — | 5.6 | Collins et al. (2000) |
| Pachic Haplustoll | L | Nebraska | 16 | 10 | mg kg$^{-1}$ d$^{-1}$ | 11 | 20 | — | 22 | Follett and Schimel (1989) |
| Mollic Cryoboralf | CL | AB, Canada | 4 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 63 | — | 42 | Franzluebbers and Arshad (1996b) |
| Typic Cryoboralf | SiL | BC, Canada | 16 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 49 | — | 50 | Franzluebbers and Arshad (1996b) |
| Typic Cryoboralf | L | BC, Canada | 7 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 50 | — | 34 | Franzluebbers and Arshad (1996b) |
| Typic Natriboralf | C | AB, Canada | 6 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 22 | — | 29 | Franzluebbers and Arshad (1996a) |
| Fluventic Ustochrept | SiCL | Texas | 9 | 5 | mg kg$^{-1}$ d$^{-1}$ | — | 11 | — | 21 | Franzluebbers et al. (1994a) |
| Typic Kanhapludult | SL | Georgia | 4 | 2.5 | mg kg$^{-1}$ d$^{-1}$ | — | 19 | — | 70 | Franzluebbers et al. (1999) |

| Soil Type | Texture | Location | Years | Depth (cm) | Units | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Udic Dystrochrept | SiL | New Zealand | 5 | 2.5 | mg $kg^{-1}$ $d^{-1}$ | 30 | — | — | 38 | Haynes (1999) |
| Typic Hapludalf | SiL | Wisconsin | 12 | 5 | mg $kg^{-1}$ $d^{-1}$ | 7 | 14 | — | 35 | Karlen et al. (1994) |
| Typic Haploboroll | SCL | AB, Canada | 16 | 15 | kg $ha^{-1}$ $d^{-1}$ | — | 11 | — | 11 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 8 | 15 | kg $ha^{-1}$ $d^{-1}$ | — | 6.9 | — | 8.6 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 9 | 15 | kg $ha^{-1}$ $d^{-1}$ | — | 18 | — | 20 | Larney et al. (1997) |
| Entic Pellustert | SC | Qld, Australia | 5 | 10 | mg $kg^{-1}$ $d^{-1}$ | — | 4.6 | — | 3.2 | Saffigna et al. (1989) |
| Typic Ochraqualf | SCL | Texas | 15 | 20 | mg $kg^{-1}$ $d^{-1}$ | 13 | 12 | — | 19 | Salinas-Garcia et al. (1997b) |
| Torrertic Paleustoll | CL | Texas | 12 | 4 | g $m^{-3\ -1}$ $d^{-1}$ | — | 16 | — | 21 | Schomberg and Jones (1999) |
| Pachic Haplustoll | L | Nebraska | 16 | 15 | kg $ha^{-1}$ $d^{-1}$ | 8 | — | — | 14 | Tracy et al. (1990) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15 | kg $ha^{-1}$ $d^{-1}$ | 26 | — | — | 31 | Wander and Bollero (1999) |
| Typic Hapludult | fSL | Alabama | 10 | 5 | mg $kg^{-1}$ $d^{-1}$ | 7 | — | — | 14 | Wood and Edwards (1992) |
| Plow vs. no tillage ($Pr > F = 0.01$) | | | | | | 11.5 | — | — | 21.9 | $n = 11$ |
| Shallow vs. no tillage ($Pr > F = 0.08$) | | | | | | | 17.4 | — | 22.0 | $n = 25$ |

**TABLE 8.9**
**Comparison of Mineralizable N in Surface Soil among Tillage Systems**

| Soil Type | Texture | Location | Years | Depth (cm) | Units | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Rhodic Kanhapludult | SCL | Georgia | 13 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.9 | — | 2.7 | Beare et al. (1994b) |
| Aridic Paleustoll | L | Colorado | 5 | 5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.31 | — | 0.36 | Burke et al. (1995) |
| Ustollic Haplargid | SL | Colorado | 5 | 5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.22 | — | 0.20 | Burke et al. (1995) |
| Typic Haploboroll | SiL | SK, Canada | 4 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.81 | — | 0.92 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 8 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.87 | — | 0.82 | Campbell et al. (1999) |
| Typic Haploboroll | SiL | SK, Canada | 12 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.75 | — | 0.73 | Campbell et al. (1999) |
| Typic Haploboroll | L | SK, Canada | 6 | 7.5 | mg $kg^{-1}$ $d^{-1}$ | — | 0.80 | — | 1.08 | Campbell et al. (1989) |
| Typic Boroll | SiL | AB, Canada | 16 | 4 | mg $kg^{-1}$ $d^{-1}$ | — | 1.02 | — | 1.45 | Carter and Rennie (1984) |
| Udic Boroll | CL | SK, Canada | 12 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.52 | — | 2.26 | Carter and Rennie (1984) |
| Typic Boroll | CL | SK, Canada | 4 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.21 | — | 1.98 | Carter and Rennie (1984) |
| Typic Boroll | L | SK, Canada | 2 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.19 | — | 1.19 | Carter and Rennie (1984) |
| Udic Pellustert | C | Qld, Australia | 13 | 10 | mg $kg^{-1}$ $d^{-1}$ | — | 4.0 | — | 5.0 | Dalal (1989) |
| Typic Paleudalf | SiL | Kentucky | 11 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | 2.4 | — | — | 3.8 | Doran (1987) |
| Aeric Ochraqualf | SiL | Illinois | 6 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | 1.5 | — | — | 2.2 | Doran (1987) |
| Aquic Hapludoll | CL | Minnesota | 6 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | 1.6 | — | — | 2.1 | Doran (1987) |
| Pachic Argiustoll | SiCL | Nebraska | 6 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | 0.9 | — | — | 1.4 | Doran (1987) |
| Pachic Haplustoll | L | Nebraska | 13 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | — | 1.0 | — | 1.1 | Doran (1987) |
| Aridic Argiustoll | SiL | Nebraska | 12 | 7.5 | kg $ha^{-1}$ $d^{-1}$ | — | 0.9 | — | 1.0 | Doran (1987) |
| Pachic Haplustoll | L | Nebraska | 16 | 10 | mg $kg^{-1}$ $d^{-1}$ | 1.4 | 1.6 | — | 1.7 | Follett and Schimel (1989) |
| Mollic Cryoboralf | CL | AB, Canada | 4 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.2 | — | 1.5 | Franzluebbers and Arshad (1996b) |
| Typic Cryoboralf | SiL | BC, Canada | 16 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.4 | — | 2.5 | Franzluebbers and Arshad (1996b) |
| Typic Cryoboralf | L | BC, Canada | 7 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 0.5 | — | 1.5 | Franzluebbers and Arshad (1996b) |
| Typic Natriboralf | C | AB, Canada | 6 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.3 | — | 1.2 | Franzluebbers and Arshad (1996a) |
| Fluventic Ustochrept | SiCL | Texas | 9 | 5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.0 | — | 2.1 | Franzluebbers et al. (1994a) |
| Typic Kanhapludult | SL | Georgia | 4 | 2.5 | mg $kg^{-1}$ $d^{-1}$ | — | 1.7 | — | 3.1 | Franzluebbers et al. (1999) |
| Solodic | SCL | Vic, Australia | 6 | 2.5 | mg $kg^{-1}$ $d^{-1}$ | — | 0.6 | — | 0.9 | Haines and Uren (1990) |
| Haplic Chernozem | fSL | Austria | 2 | 10 | mg $kg^{-1}$ $d^{-1}$ | 4.4 | 5.4 | — | 6.5 | Kandeler et al. (1999) |
| Haplic Chernozem | fSL | Austria | 6 | 10 | mg $kg^{-1}$ $d^{-1}$ | 2.9 | 7.2 | — | 7.4 | Kandeler et al. (1999) |
| Haplic Chernozem | fSL | Austria | 8 | 10 | mg $kg^{-1}$ $d^{-1}$ | 2.1 | 6.4 | — | 8.3 | Kandeler et al. (1999) |

| Soil Type | Texture | Location | Years | Depth (cm) | Units | Plow | Shallow | Ridge | No. | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Typic Haploboroll | SCL | AB, Canada | 16 | 15 | mg $kg^{-1}$ $d^{-1}$ | — | 0.60 | — | 0.63 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 8 | 15 | kg $ha^{-1}$ $d^{-1}$ | — | 0.45 | — | 0.52 | Larney et al. (1997) |
| Typic Haploboroll | SCL | AB, Canada | 9 | 15 | kg $ha^{-1}$ $d^{-1}$ | — | 0.88 | — | 0.97 | Larney et al. (1997) |
| Aquic Hapludult | SiL | Maryland | 18 | 2.5 | mg $kg^{-1}$ $d^{-1}$ | 0.46 | — | — | 1.21 | McCarty and Meisinger (1997) |
| Aquic Hapludult | SiL | Maryland | 21 | 2.5 | mg $kg^{-1}$ $d^{-1}$ | 0.29 | — | — | 0.71 | McCarty and Meisinger (1997) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 5 | mg $kg^{-1}$ $d^{-1}$ | 3.0 | — | — | 4.5 | Needelman et al. (1999) |
| Entic Pellustert | SC | Qld, Australia | 5 | 10 | mg $kg^{-1}$ $d^{-1}$ | — | 0.36 | — | 0.53 | Saffigna et al. (1989) |
| Typic Ochraqualf | SCL | Texas | 15 | 20 | mg $kg^{-1}$ $d^{-1}$ | 0.95 | 0.90 | — | 1.32 | Salinas-Garcia et al. (1997b) |
| Torrertic Paleustoll | CL | Texas | 12 | 4 | g $m^{-3\ -1}$ $d^{-1}$ | — | 0.72 | — | 0.64 | Schomberg and Jones (1999) |
| Humic Gleysol | L | QC, Canada | 3 | 7.5 | mg $kg^{-1}$ $d^{-1}$ | 1.0 | 1.4 | — | — | Simard et al. (1994) |
| Pachic Haplustoll | L | Nebraska | 16 | 15 | kg $ha^{-1}$ $d^{-1}$ | 0.9 | — | — | 1.5 | Tracy et al. (1990) |
| 36 (Argiudoll-Argiaquoll) | SiCL | Illinois | >5 | 15 | kg $ha^{-1}$ $d^{-1}$ | 8.3 | — | — | 8.5 | Wander and Bollero (1999) |
| Typic Hapludult | fSL | Alabama | 10 | 5 | mg $kg^{-1}$ $d^{-1}$ | 0.43 | — | — | 0.83 | Wood and Edwards (1992) |
| Plow vs. shallow tillage ($Pr > F = 0.10$) | | | | | | 2.1 | 3.8 | — | — | $n = 6$ |
| Plow vs. no tillage ($Pr > F = 0.01$) | | | | | | 2.1 | — | — | 3.5 | $n = 15$ |
| Shallow vs. no tillage ($Pr > F < 0.01$) | | | | | | | 1.6 | — | 2.0 | $n = 31$ |

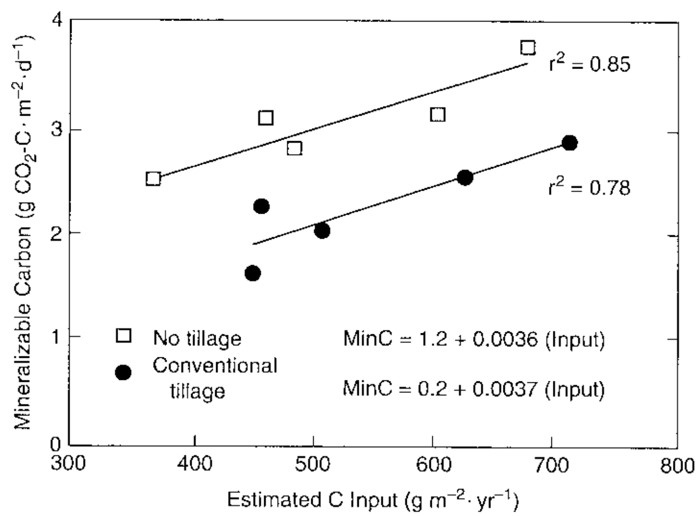


**FIGURE 8.20** Mineralizable C as a function of C input among five cropping systems under conventional and no tillage in southcentral Texas. (Data from Franzluebbers, A.J. et al. 1998. *Soil Tillage Res.* 47:303–308.)

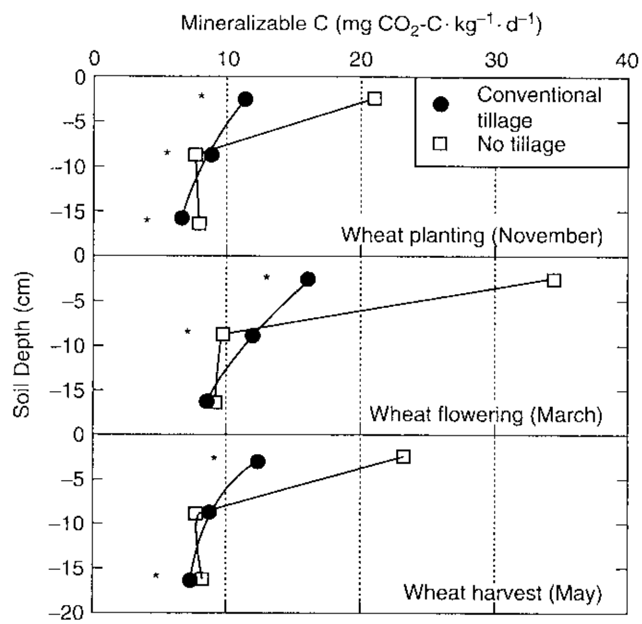


**FIGURE 8.21** Depth distribution of mineralizable C sampled at three growth stages of wheat under conventional and no tillage in southcentral Texas. * indicates significance between tillage systems at $p < 0.1$. (Data from Franzluebbers, A.J. et al. 1994b. *Soil Biol. Biochem.* 26:1469–1475.)

tillage is on earthworms. Earthworms require a moist environment with adequate organic debris, both provided by conservation tillage. In a Typic Rhodudult in Georgia, earthworms, microarthropods and various macroarthropods were two- to several-fold more numerous under no tillage than under conventional tillage as a result of the stratification of organic debris near the soil surface (House and Parmelee, 1985).

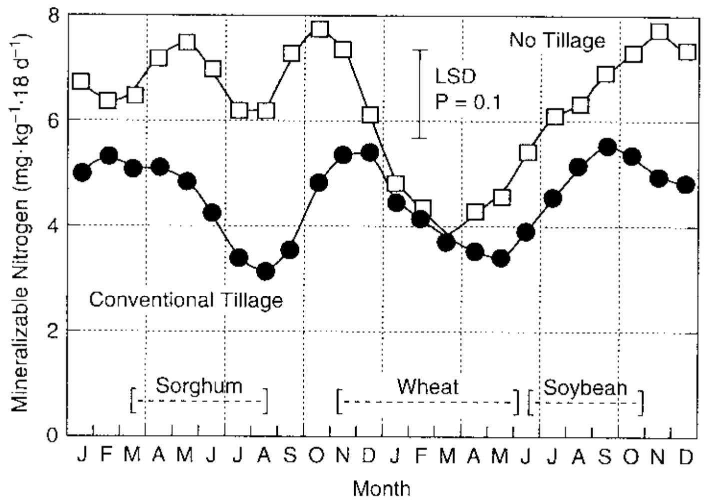


**FIGURE 8.22** Mineralizable N on a monthly basis during the ninth and tenth year under conventional and no tillage in southcentral Texas. (Data are from 3-month running averages reported in Franzluebbers, A.J., et al. 1996b. *Z. Pflanzenernähr. Bodenk.* 159:343–349.)

## SOIL ORGANIC MATTER AFFECTED BY INTERACTION OF TILLAGE WITH CROPPING INTENSITY

Sequestration of soil organic C is dependent on the net balance between C inputs and C outputs. Crop rotation and the intensity of cropping can affect the quantity and quality of organic inputs. The type of tillage management along with cropping intensity can also affect the decomposition environment, resulting in altered C output. Comparisons of continuous wheat with wheat–fallow rotations under shallow tillage and no tillage are most abundant in the literature. At the end of 12 years of tillage management on a Haploboroll in Saskatchewan, soil organic C at a depth of 0 to 15 cm was 0.05 kg $m^{-2}$ higher under no tillage than under shallow tillage in wheat–fallow and 0.14 kg $m^{-2}$ higher under no tillage in continuous wheat (Campbell et al., 1995). At the end of 11 years on a Typic Haploboroll in Saskatchewan, soil organic C at a depth of 0 to 15 cm was 0.06 kg $m^{-2}$ higher under no tillage than under shallow tillage in wheat–fallow and 0.18 kg $m^{-2}$ higher under no tillage in continuous wheat (Campbell et al., 1996). However, the difference in soil organic N between no tillage and shallow tillage was similar, whether the crop rotation was wheat–fallow ($\Delta$13 g $m^{-2}$) or continuous wheat ($\Delta$11 g $m^{-2}$). At the end of 9 years on a Typic Haploboroll in Alberta, no tillage had greater positive effects on mineralizable C and N in continuous wheat than in wheat–fallow (Larney et al., 1997). However, no tillage had greater positive effects on soil organic C and N and light-fraction C and N in wheat–fallow than in continuous wheat. At the end of 6 years on a Typic Argiboroll in North Dakota, soil organic C to a depth of 30 cm was 0.68 kg $m^{-2}$ lower under no tillage than under conventional tillage in wheat–fallow, but 0.64 kg $m^{-2}$ higher under no tillage in a wheat–wheat–sunflower rotation (Black and Tanaka, 1997). Soil organic N responded similarly to soil organic C: no tillage was 52 g $m^{-2}$ lower in wheat–fallow and 41 g $m^{-2}$ higher in wheat–wheat–sunflower. At the end of 7 years on a Torrertic Paleustoll in Texas, soil organic C under no tillage was 0.09 kg $m^{-2}$ higher than under stubble-mulch tillage in wheat–fallow and 0.13 kg $m^{-2}$ higher under no tillage in continuous wheat (Jones et al., 1997). Wheat–fallow has been utilized in the Great Plains region of North America, where precipitation is low and variable, to reduce risk of crop failure by filling the soil profile with water during the fallow period. However, precipitation use efficiency is improved with no-tillage management such that the fallow phase might not be economically productive compared with more intensive cropping (Peterson et al., 1996). In wheat–fallow, no tillage can keep the surface soil moister during the fallow phase such that organic matter decomposition is enhanced compared with the more extreme drying of the surface soil with tillage.

In warm, moist climates, more intensive cropping can make better use of environmental conditions by producing plant biomass throughout the year. Increased cropping intensity might increase the risk of a particular crop failure, but with extended time will likely capture more opportunities for enhanced C input via photosynthetic fixation. At the end of 9 years on a Fluventic Ustochrept in Texas, soil organic matter pools were always higher under no tillage than under conventional tillage, irrespective of cropping intensity (Figure 8.23). Absolute changes in soil organic matter pools with respect to tillage system were similar among all cropping intensities, suggesting no significant interaction between tillage system and cropping intensity on soil organic matter pools. However, the soil organic C sequestration rate per unit of estimated C input was significantly higher under no tillage than under conventional tillage at low cropping intensities (Figure 8.23).

## SOIL ORGANIC MATTER AFFECTED BY INTERACTION OF TILLAGE WITH SOIL TEXTURE

Soil texture might alter the response of soil organic matter pools to tillage management by altering plant productivity, soil moisture retention, and community structure and activity of soil organisms, all of which could have impacts on C inputs and outputs. Irrespective of tillage management, fine-textured soils, especially dominated by montmorillonitic clays, can store higher quantities of organic matter than can coarse-textured soils (Nichols, 1984; Hassink, 1994; Needelman et al., 1999). In a survey of 36 fields in Illinois, whole-soil and particulate organic C and N were higher under no tillage than under conventional tillage when sand content was <10% at a depth of 0–5 cm, but lower under no tillage when sand content was >10% at a depth of 5–15 cm (Needelman et al.,

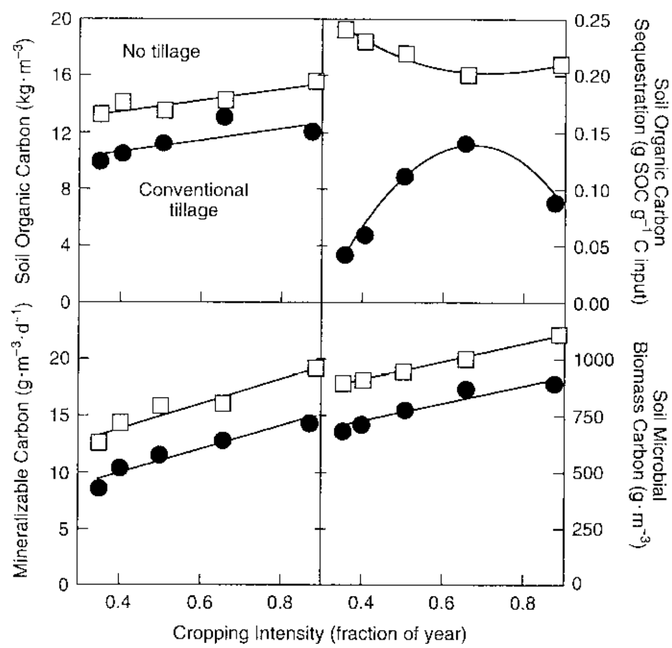


**FIGURE 8.23** Soil organic matter pools at the end of 9 years of conventional and no tillage among five cropping systems that formed a cropping intensity gradient in southcentral Texas. (Data from Franzluebbers, A.J., Hons, F.M., and Zuberer, D.A. 1998. *Soil Tillage Res.* 47:303–308.)

1999). When the surface 15 cm was considered as a whole, soil and particulate organic C and N were not affected by the interaction of tillage and texture. From a set of four soils along a textural gradient in northern Alberta and British Columbia, tillage interacted with texture such that total, particulate, and microbial biomass C were not different between tillage systems in soils with low clay content, but were higher under no tillage than under conventional tillage in soils with high clay content.

According to a compilation of tillage studies on different soils, soil organic C storage with no tillage compared with conventional tillage was significantly higher in silty clay loams than in loams (Franzluebbers and Steiner, 2002). Overall, available data suggest that sequestration of soil organic C with no tillage compared with conventional tillage within the surface rooting zone might be higher in soils with finer texture.

## SOIL ORGANIC MATTER AFFECTED BY INTERACTION OF TILLAGE WITH CLIMATIC REGION

The climatic conditions of a region dictate to a large extent the type and sequence of crops grown. How the crops are managed can vary to some extent, such as crop variety selection, type and quantity of fertilization, type of pesticide applications, timing of planting, and type of tillage system employed. In some regions, forms of conservation tillage have been employed for many years, such as stubble-mulch tillage in the Great Plains of the U.S. or shallow blade or disk tillage in the western wheat region of Canada. These systems have become the convention rather than the exception.

According to a compilation of tillage studies from North America, the change in soil organic C with no tillage compared with conventional tillage was greatest when sites were located in the mesic subhumid region with a mean annual precipitation to potential evapotranspiration ratio of 1.4 to 1.6 mm $mm^{-1}$ (Figure 8.18). The relationship of the change in soil organic C with climate was not particularly strong, probably because the data were too limited to clearly separate cropping intensity, soil textural, and other management differences that might have interacted with climate. However, the derived shape of the response with climate is logical. Minimal benefit of no tillage on soil organic C storage compared with conventional tillage could be expected in dry, cold regions, because low precipitation would limit the potential of plants to fix C and limit decomposition even when crop residues are mixed with soil with tillage. In relatively wet, hot regions of North America, the benefit of no tillage on soil organic C storage compared with conventional tillage might also be limited, because abundant precipitation combined with warm temperature would allow surface-placed residues an ideal environment for rapid decomposition, similar to that with tillage. More long-term tillage studies under different soil and climatic conditions are clearly needed to accurately understand the dynamics of soil organic matter under the wide diversity of environments in the world.

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